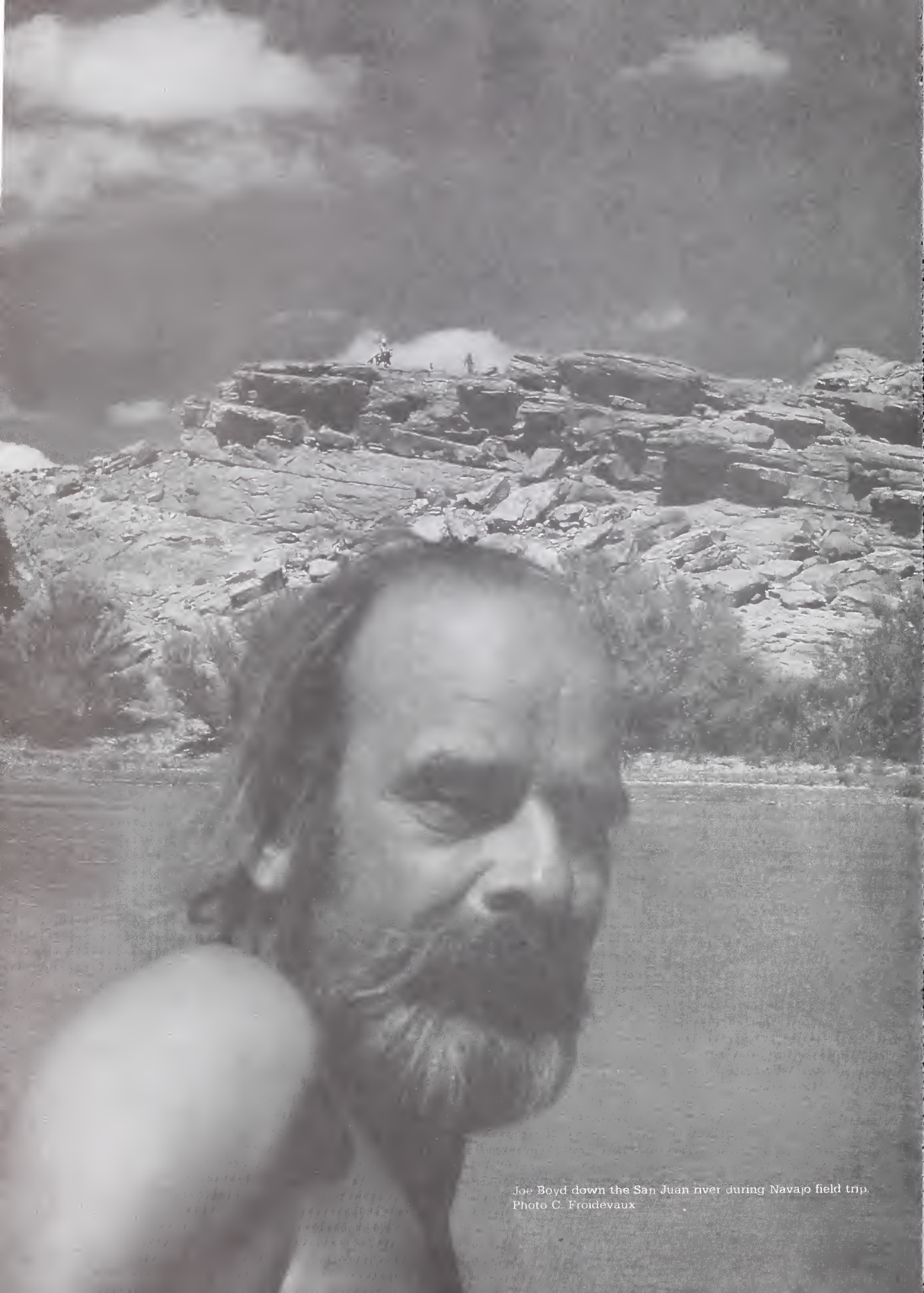# Third international KIMBERLITE conference

Clermont-Ferrand

Joe Boyd down the San Juan river during Navajo field trip.
Photo C. Froidevaux

KIMBERLITE CONFERENCES

PEOPLE are sometimes perplexed on discovering that Kimberlite Conferences have no perpetuating, formal organization. There is no international Council that oversees plans for field trips or establishes the format for meetings. There is no election or appointment of Convenors. Kimberlite Conferences are arranged entirely outside the protocol of IUGG or IUGS. There is not even a committee that decides when and where a Kimberlite Conference shall be held !

This remarkable informality is not inefficient ; in fact, it provides invaluable flexibility to Conference arrangements. Scientific discussions can be set up in whatever manner seems most likely to provide the best communication. Field trips of great diversity and complexity can be arranged by involving any needed persons, regardless of affiliation. The informality does, however, put a heavy load on those who design and manage the local arrangements. Organizing a Kimberlite Conference is a challenging job !

THE petrological and geochemical research presented at Kimberlite Conferences grows continually more sophisticated and our knowledge of kimberlite eruptions and the petrologic structure of the upper mantle grows steadily more complete. The question of whether or not garnet peridotite inclusions in kimberlites are cognate was still open at the time of the Cape Town Conference. Today the coarse peridotites are generally accepted to be xenoliths and petrologists have increasing confidence in estimates of their depths and temperatures of equilibration. Striking deformation textures exhibited by some peridotite xenoliths are now understood to have developed during the initial stages of eruption. Also the lithologic complexity of the real mantle – in contrast to model mantles - is much better appreciated.

MUCH emphasis has been placed on field trips associated with Kimberlite Conferences because of the collecting opportunities they afford and because discussion among geologists is often much better on outcrop or in camp than it is in formal meeting rooms. After the Cape Town Conference a group of eighty participants ventured up the precipitous Moteng pass into the Lesotho highlands. Melting snow turned the tracks into quagmires. Nevertheless, the group visited such remote kimberlites as Thaba Putsoa, Matsoku and Kao. All Landrovers were returned safely to Maseru and only one geologist was lost (temporarily) !

During the Navajo trip preceding the Santa Fe Conference the group ran the San Juan canyon in rafts to visit the Mule Ear diatreme. A drought reduced the river to puddles but the Bureau of Reclamation was persuaded to open the Navajo dam, upstream from the diatreme.

Unfortunately, the anticipated flood arrived a day late and participants were forced to do much wading and dragging of rafts and equipment. Incredibly, this disaster turned into a race and delegates arrived at Mule Ear convulsed with laughter.

THE above will suggest that Kimberlite Conferences require a certain amount of fortitude. They do, but those fortunate to have come to Clermont Ferrand and to have participated in the Moho and Volcano field trips will have been richly rewarded. We have learned much but many questions remain in this exciting science. Perhaps we will soon more fully understand the circumstances under which diamonds crystallize and the tectonic events that lead to kimberlite eruptions.

F.R. Boyd

The 1977 Navajo field trip : dinner at Bluff, Utah.
Photo C. Froidevaux

A

Diamonds

A1
SOME OBSERVATIONS RELEVANT TO THE FORMATION OF NATURAL DIAMONDS

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Apparent old ages for some diamonds in cretaceous kimberlite support a non-cognate diamond paragenesis. Calculated equilibrium conditions for peridotitic inclusions in diamonds closely match those for coarse peridotite xenoliths in Kimberlite, though the latter rarely contain diamonds. The P/T estimates lie close to calculated shield geotherms and the peridotite solidus. The lowest temperatures for inclusion pairs imply sub-solidus crystallisation. In contrast observations of growth spirals on octahedral diamonds and of poly crystalline nuclei inside diamonds favours metasomatic or igneous growth. He isotopic ratios favour a mantle origin and argue against subduction models.

The release of diamond into kimberlite by disaggregation of xenoliths may sometimes be important but in general neither the relative abundance nor the chemistry of diamond inclusions correlates well with mantle xenoliths found at a specific locality. Most inclusions in diamonds have a harzburgitic paragenesis with distinctive mineral chemistry compared to peridotite xenoliths. Macrocryst minerals in diamondiferous kimberlite fill the compositional gap between the inclusions and coarse grained xenoliths. This does not fit a simple disaggregation model.

Whilst the peridotitic and eclogitic inclusion parageneses have often been regarded as discrete processes their ubiquitous association and their compositional continuity at some localities suggests a related origin.

Some of these observations are irreconcilable so that neither primordial mantle, nor mantle melting nor crustal subduction models are entirely convincing, leaving the relationship of diamond to kimberlite unresolved.

A2
THE GENESIS OF DIAMOND

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During the last decade or so a large amount of information pertaining directly or indirectly to the formation of diamond in nature has become available. The numerous studies of the mineral chemistry of xenoliths in kimberlite, as well as the studies of kimberlite and of inclusions in diamond provide the bulk of the information.

Early chemical analyses of inclusions in diamonds indicated the overall similarity of mineral types from worldwide localities and differing geological ages. However, the most important aspect of the early studies was the recognition that diamonds form in two geochemically distinct environments - one ultramafic and one eclogitic. This simple division although still valid in a general way, needs modification in the light of recent observations of inclusion chemistry and diamond occurrence. It appears most likely that within the upper mantle carbon is in the form of diamond and that this latter mineral can exist in several rock types within the broad subdivision of eclogite and ultramafic types.

The occurrence of diamond in kimberlite or other rock types is due to the speed and mode of transportation of the diamond to the earth's surface and thus it is highly unlikely that diamond is a phenocryst in kimberlite.

A3
ABUNDANCES OF CARBON IN MANTLE XENOLITHS FROM ALKALIC BASALTS

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In mantle xenoliths from volcanic rocks, C exists as CO_2 in fluid inclusions and as an elemental form in microcracks and on inclusion walls. Carbonate is usually present as well and is generally believed to have been introduced after eruption. Both absolute amounts of C and relative abundances of its various forms were determined in a suite of representative xenoliths. Interior portions of samples were crushed to coarse (<1.4 mm) fragments, washed in cold 1N HCl, and fused with a flux. Fusion in an oxidizing atmosphere liberated all elemental C and vapor as CO_2, which was then determined by titration. In contrast, only vapor was liberated from samples fused in a reducing atmosphere. A similar procedure was followed for unwashed samples.

A significant proportion of the C in nearly all samples is removed by acid-washing. The soluble fraction must reside on grain boundaries and is presumed to be carbonate. In samples collected from environments in which caliche is present, carbonate contamination from meteoric sources is suspected. In others, carbonate probably also originated by post-eruptive redistribution of C from host lavas.

Most acid-washed Cr-diopside spinel lherzolites contain 10-40 ppm (by wt.) total C. These concentrations are considerably lower than those determined from previous analyses. The range in C contents of four Al-augite pyroxenites is 40-80 ppm, and one of the amphibole-phlogopite-apatite-spinel lherzolites from Nunivak Is., Alaska contains 85 ppm C.

The average $C:CO_2$ ratio for all samples is 0.06. Assuming that elemental C results from the reaction $2CO \rightarrow C + CO_2$, then the vapor from which C precipitated consisted of $\sim$30 mole % CO.

A4

DIAMOND CHARACTERISTICS OF THE DE BEERS POOL MINES, KIMBERLEY, SOUTH AFRICA

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Diamonds from the four operating mines at Kimberley (Bultfontein, De Beers, Dutoitspan, Wesselton), have been examined using a classification scheme which quantifies, as a function of specific diamond size classes, such physical characteristics as crystal form, colour, ultra-violet fluorescence, and plastic deformation. In addition, from a single size class, the relative abundances of syngenetic silicate, oxide and sulphide minerals in the diamonds have been determined.

The results from the classification indicates that, in general, there is usually <10% variation in the proportion of primary crystal forms between the four mines, although secondary crystal forms show more pronounced variations. Diamond colour is broadly similar for the four mines but the proportions of the principal colours (colourless, yellow, brown) are distinctive at each mine. The numbers of fluorescent diamonds are typically low, levels varying between 5-10% in the small sizes to 20-40% among the larger stones. The principal fluorescent colour is weak blue, other minor colours being strong blue, green, orange and yellow. Blue and strong blue fluorescence are distinctive for diamonds from De Beers and Wesselton, respectively. Plastic deformation levels for the four mines are also distinctive but levels are independent of diamond size. Inclusion studies indicate that the diamonds from all four mines have a dominant (90% plus) 'peridotitic' paragenesis, with a particularly high chromite inclusion content.

Differences in characteristics can separate diamonds from the four Kimberley mines, but those characteristics which can reasonably be associated with diamonds' formation are closely similar, which is compatible with the Kimberley diamonds being derived from a single diamond population.

A5

A TRANSMISSION ELECTRON MICROSCOPY STUDY OF OLIVINE INCLUSIONS IN DIAMOND

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Olivine inclusions in elasticity isotropic diamond (cubic anisotropy factor $A = 2C44/C11 - C12 = 1.54$) have been studied with a view to obtaining information about olivine dislocation substructure under mantle conditions. Olivine inclusions 0.05- 0.3 mm in diameter have been extrated by combustion from a diamond from the UDACHNAYA pipe, Yakatia, USSR. Individual inclusions have been mounted on cooper grids and ion thinned at 5 KV for T.E.M. examination in a JEOL microscope at 120 KV.

A low dislocation density of less than $10^4 cm^{-2}$ is observed. To obtain the maximum information from the few dislocations observed, the dislocation images have been recorded under diffracting conditions of g.b = 0, 1, 2 where g is the diffracting vector and b is the Burgers vector. Straight mixed free dislocations are present with both [001] and [100] Burgers vectors. Heated fractures on the (010) plane are observed with [100] loops and [001] straight dislocations.

The above observations are consistent with the low stress and high temperatures thought to prevail in the mantle. No evidence of a subsequent high stress crustal deformation is observed.

A6

THE ABUNDANCE AND CHEMISTRY OF MINERALS ASSOCIATED WITH DIAMONDS AT ROBERTS VICTOR MINE

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A study of minerals in diamonds has shown that their abundance and chemistry are at gross variance with the xenolith mineralogy at the Roberts Victor Mine. The latter is $>$95% eclogitic.

Olivine and associated minerals predominate ($\sim$85%) in diamond. The most abundant paragenesis is harzburgitic (ol,opx,$\pm$chr$\pm$gar). There is a small garnet lherzolite field (+cpx). The above minerals are similar to peridotitic inclusions world wide; (high Mg/Fe,Cr_2O_3, low CaO). An exception is that opx usually has a higher Al_2O_3 ($>$1wt%) and Cr_2O_3 ($>$0.5wt.%). Two gar/ol pairs give high equilibration temperatures $>$1300°C, but a cpx (Ca/Ca+Mg=0.45) probably equilibrated at $\sim$1100°C.

Eclogitic gar and cpx are subordinate ($\sim$15%) to peridotitic inclusions. Sulphide occurs in both associations and a single felspar of presumed eclogitic affinity is the only other mineral found in 166 diamonds.

There is a large compositional gap between the peridotitic and eclogitic inclusion minerals. The latter are characterised by high Fe/Mg, TiO_2, Al_2O_3, CaO, Na_2O and K_2O and by lower Cr_2O_3. The garnets are $\sim$65% almandine, and fall outside the compositional field for Rovic eclogite (Hatton 1978). The cpx show a positive MgO/Cr_2O_3 correlation; negative for MgO/Al_2O_3, MgO/Na_2O and MgO/K_2O.

Since the predominant diamond inclusion is per-
idotitic and the rarer eclogitic inclusions are
chemically discrete from the xenoliths this
study suggests that most of the diamonds at
Roberts Victor are not derived from disaggre-
gated eclogite. Some could be related to rare
garnet peridotite and chromite peridotite also
described by Hatton (1978).

A7

INCLUSIONS IN DIAMONDS FROM EASTERN KA-SAI, ZAIRE.

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Zaïre is probably the major diamond produ-
cer outside the USSR and Australia yet little
is available in the scientific literature
concerning the mineralogy and geochemistry of
kimberlites, diamonds and associated xenoliths
Probably this lack of information is due to
the fact that the major portion of the diamond
output of Zaïre is industrial grade material.
Nevertheless, the geographic position of Zaïre
in the central part of southern Kapvaal cra-
ton, which has received much attention, makes
it an important locality for mantle and rela-
ted studies. Accordingly, a preliminary in-
vestigation of diamond inclusions, megacrysts
and xenoliths has been undertaken from Mbuji
Mayi and Tshibua in Eastern Kasaï, Zaïre.

About 200 diamonds from Eastern Kasaï were
examined for mineral inclusions. Olivine, gar-
net, cpx, kyanite, rutile, zircon, chromite,
ilmenite, pyrrhotite, diamond and bimineralic
assemblages garnet+cpx are recorded as prima-
ry inclusions. Goethite, graphite and hemati-
te are probably epigenetic while quartz is of
uncertain origin.

In contrast to many localities, olivine is
not an abundant mineral in the diamonds se-
lected. No enstatite is recorded.
Instead garnet and cpx are the most abundant
silicates in these samples. Both these latter
belong to either lherzolitic or eclogitic
suites. The first occurrence in the world of
jadeitic cpx as inclusion in diamond is re-
corded. Jadeitic cpx, kyanite and diamond
outline a new paragenetic suite for inclu-
sion called "kyanite eclogite", "grospydite"
or "diamond eclogite". Pyrrhotite with fine
intergrowths of pentlandite(?) forms the most
abundant inclusion in the examined diamonds.

A8

THE ABUNDANCE, MINERALOGY AND CHEMISTRY OF SULPHIDE INCLUSIONS IN DIAMONDS

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A study of the abundances of sulphide inclus-
ions in diamond has enabled a detailed electron
microprobe examination of these minerals to be
completed as part of a general evaluation of this
impurity in natural diamonds from worldwide occu-
rrences. The work has concentrated on sulphides
in diamonds from specific southern African kim-
berlites (e.g. Premier, Finsch, Jagersfontein,
Orapa, Roberts Victor), but sulphide inclusions
in diamonds from kimberlites in Sierra Leone and
in East Africa are also reported.
Inclusion abundance tables show that sulphides
are often the commonest mineral type (over 40%).

The iron-nickel sulphide minerals identified are
monosulphide solid solution, pyrrhotite, pent-
landite, pyrite and heazlewoodite, and copper
sulphides, chalcopyrite, cubanite and probably
cubanite solid solution. A wide variety of
mineral assemblages have been found within the
polished mounts of single inclusions of sulphide,
several being specific to diamonds from specific
kimberlites (e.g. the m_{ss} assemblages from the
Koffiefontein mine.) Some chemical features of
these minerals are:- (i)m_{ss}:- variable Fe/Ni+Co
ratio (15.0-1.3) with majority of data cluster-
ing about 6.6, (ii)po:- typically contains 0.2-
0.5 at.% Ni+Co with 0.1 at.% Cu, (iii)pn:- in-
variably nickeliferous (26.5-30.0 at.% Ni+Co)with
0.1-0.2 at.% Cu, (iv)cp:- close to stoichiometry
approx. 0.1 at.% Co, variable Ni (0.02-0.06at.%),
(v)py:- few good analyses but seems to be Cu-
enriched (0.2-0.3 at.%) with 1.2-1.5 at.% Co and
0.02-0.06 at.% Ni, (vi)cb:- analyses cluster
around cb with >1.0 at.% Ni+Co.

The sulphide mineralogy is linked to both the
'peridotitic' and 'eclogitic' growth environments
of diamond and these results provide information
about sulphide geochemistry in the Earth's upper
mantle and is the case of Koffiefontein data on
the emplacement history of this kimberlite.

A9

SILICATE AND OXIDE INCLUSIONS IN DIAMONDS FROM ORAPA MINE, BOTSWANA.

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In approximate order of decreasing abundance
sulphides, garnet, clinopyroxene, chromite
orthopyroxene and olivine occur as inclusions in
Orapa diamonds. One coesite has been identified.
Except for the olivines (Fo_{92-94}), the common
minerals show a wide range in chemistry; from a
low calcium, high Mg, harzburgitic assemblage
(ol,opx+gar+chr); an inferred small lherzolite
field; a websterite field (opx,cpx,gar+chr.); an
eclogite field (cpx,gar)terminating with high
calcium garnets and jadeitic clinopyroxenes typ-
ical of kyanite eclogite. Chromium shows a pos-
itive, and sodium a negative correlation with
MgO. Potassium in clinopyroxene ranges unsystem-
atically up to 1.2 Wt.% Orthopyroxene and clino-
pyroxene buffer the calcium content of garnet.
Calcium enrichment of garnet only occurs in the
absence of opx, and calcium depletion only in
the absence of cpx. Mineral compositions in
single diamonds and tie lines for co-existing
phases indicate that inclusions approximate
equilibrium assemblages. Geothermometry tenta-
tively suggests T of formation within an interval
of 150°C and close to 1150°C. The inclusions are
restricted to an iron rich sector of the overall
eclogite xenolith field although xenoliths out-
side the inclusion field can contain diamonds.
The websterite field is expanded in the diamonds
relative to the xenoliths.

The inclusion suite is unusual for southern
Africa because (i) Eclogitic and websteritic
mineral compositions predominate over peridotitic
by more than 10:1 (ii) There is no readily
apparent compositional gap between the peridoti-
tic and non-peridotitic associations (iii) The
orthopyroxenes have a wide range in Mg/Fe ratio
and (iv) Chromites are relatively common.

A10

THE RELATIONSHIP BETWEN INCLUSION COMPO-SITION AND CARBON ISOTOPIC COMPOSITION OF HOST DIAMOND

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The ^{13}C content of the diamonds from the Premier and Fisch kimberlite is not related to diamond shape, color, state of deformation, type of mineral or the type of mineral paragenesis included. For the Premier mine it could be demonstrated that inclusion containing and inclusion free diamonds have the same mean $\delta^{13}C$ value. However, an isotopic composition difference between diamonds from Premier and Finsch kimberlites is observed, and in both occurrences there is a distinct association of diamonds of higher ^{13}C contents with inclusions low in SiO_2 (olivine, eclogite suite garnets and clinopyroxenes), Al_2O_3 (orthopyroxenes, peridotite suite garnets, eclogite suite garnets and clinopyroxenes), Cr_2O_3 (olivine, orthopyroxene, peridotite suite garnets, eclogite suite clinopyroxenes), MgO and Mg/(Mg+ Fe), (clivines, orthopyroxenes, peridotite suite garnets, eclogite suite garnets), Na_2O, K_2O, TiO_2 (eclogite suite clinopyroxenes) and high in FeO (olivines, orthopyroxenes, and peridotite suite garnets), CaO (peridotite suite garnets, eclogite suite garnets and clinopyroxenes) and Ca/(Ca+Mg) (eclogite suite garnets and clinopyroxenes). Mg-Fe partitioning between ultramafic suite minerals occluded by the same diamond indicates higher pressure and temperature conditions of equilibration for diamonds with $\delta^{13}C$ larger than -4 o/oo and essentially peridotite subsolidus conditions for those with lower $\delta^{13}C$ values. For eclogite type inclusions, equilibration conditions in excess of 1100°C and 140 km depth are deduced and no further separation of carbon isotopic composition according to equilibration conditions was observed. The data are interpreted to indicate that in the mantle zones exist in which the average $\delta^{13}C$ value of carbon is above -4 o/oo and that these zones lie below about 140 km depth

A11

DIAMOND AND GRAPHITE ECLOGITE FROM ORA-PA

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Orapa eclogite xenoliths are unique for the relative abundance of diamond eclogite (∽0.7%) and graphite eclogite (∽4.6%). The diamonds closely resemble mine production in colour, the common presence of interpenetrant twins and of aggregates. They differ in that octahedral growth forms are well preserved. The graphite is euhedral and tabular.

Mineral analyses confirm previous studies that diamond eclogites have a wide range of compositions. They tend to be calcium rich compared to inclusions in Orapa diamonds. There is only minor overlap of the two fields. The large garnet websterite field in the diamonds is rare in the diamondiferous rocks. Framesite minerals are contrastingly common in this region of the inclusion field. Minerals intergrown with coarser grained polycrystalline aggregates of diamond are more frequently similar to diamond eclogite minerals. This suggests slower growth is associated with calcium rich eclogite minerals.

Clinopyroxene in diamond from an eclogite is markedly less jadeitic than clinopyroxene in the host rock. This and other observations in mineral inclusions suggests the formation of the magnesian eclogites before the high iron and calcium types.

Graphite eclogites form two chemical groups, one with garnets of high Mg/Fe similar to garnet websterite xenoliths; the seond larger group form a narrow compositional band across the diamond eclogite field chiefly the result of a wide variation in Ca/Fe ratio.

Attempted application of the Ellis and Green (1979) geothermometer fails to account for the observed distribution of carbon phases as a temperature effect.

Ref : Ellis, D.J. and Green D.H. (1979) Contrib. Mineral Petrol. 71, 13-22.

B   Kimberlites: where?

EVALUATION OF GEOPHYSICAL TECHNIQUES FOR DIATREME DELINEATION IN THE COLORADO-WYOMING KIMBERLITE PROVINCE

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Kimberlite diatremes in northern Colorado and southern Wyoming are generally characterized by poor exposure due to truncation by erosion surfaces and presence of ubiquitous colluvial and(or) soil cover. Ground geophysical methods may be used in conjunction with geological mapping to delineate diatreme contacts. Magnetic surveys reveal that most diatremes are characterized by small positive dipolar anomalies. Convolution of magnetic data and removal of regional magnetic gradients allow for delineation of diatreme boundaries. Electrical resistivity and conductivity (electromagnetic) surveys show that kimberlitic soils are generally 5-10 times more conductive than granitic soils. The broadside EM method was effective for locating kimberlite contacts in areas of modest soil cover whereas kimberlite covered by as much as 25 meters of surficial material could be detected using the VLF method. Radioactivity surveys were effective only in areas where soil cover is thin to absent. Gravity and refraction seismic methods were ineffective in determining diatreme contacts because of a common lack of appreciable contrasts in density and elasticity of kimberlite and host granites. Magnetic, electrical resistivity, and electromagnetic methods clearly are the most effective geophysical techniques tested for delineating kimberlite contacts in the Colorado-Wyoming kimberlite province. (Study supported by grants from the Rocky Mountain Energy Company and the Geological Soc. of America)

A TELEDETECTIVE STUDY OF KIMBERLITE REGIONS IN N. AMERICA, E. AFRICA, AND SIBERIA

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Teledetective evaluation involves the integrated use of remote sensing, geomorphological and geo-physical data planes to depict the surface and subsurface character of provinces that occur in extremely different environments. Study areas in Colorado-Wyoming, Tanzania and Yakutia were chosen on the basis of their diversity: e.g. elevation (2400m, 1200m, 300m, respectively), climate (temperate, equatorial, arctic), country rock (granite, granite, limestone), and floral cover (montane forest, grassland, taiga). Through the analysis of similarly scaled Landsat images (infrared reflectance), aeronautical maps (drainage patterns and topography), and geophysics (mass distribution and magnetic variation), the teledetective approach permits several related but distinct aspects of a given kimberlite province to be considered simultaneously and to be compared to other known or suspected kimberlite provinces, in terms of tectonic grain and specific textural and(or) structural features.

The technique indicates that the Colorado-Wyoming State Line Kimberlite District, the Mwadui region, and the Mir region all seem to be characterized by some type of cross-cutting textural signature where the regional trend is interrupted or intersected by another trend. Pretorius (1981) suggests that diamondiferous kimberlites in southern Africa tend to occur at the intersection of extensive anteclisal concentric and radial patterns. Assuming that the textural interference patterns observed in this study also reflect deep-seated zones of structural disturbance (e.g. intersecting fault systems) that could provide conduits for the ascent of kimberlite magma, such features may have value in delineating favorable target areas in kimberlite exploration programs.

GEOBOTANICAL EXPRESSION OF A BLIND KIMBERLITE PIPE, CENTRAL INDIA

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Vegetation growing over a blind kimberlite pipe in central India was employed to explore the possibility of using it as an additional tool for searching hidden kimberlite pipes in areas indicated by geophysical prospecting. Hinota pipe (24°39'N: 80°02'E) intrusive into the Precambrian quartz arenite is largly in an undisturbed state and is therefore an appropriate choice for this study.

Whereas the undergrowth over the quartzitic

country rock is scanty, only about 10-20 cm high, it attains heights of 50-100 cm over the pipe area. Among the larger trees, the covered pipe supports not only more species but also a more luxuriant and healthy growth in contrast to the surrounding terrain. Among the 26 species recorded over the pipe area, Tectona grandis, Diospyres melanoxylon and Madhuca indica attain a general height of 11.0, 8.6 and 11.1 metres respectively in contrast to 7.6, 5.6 and 5.0 metres for the same species growing outside the pipe area. The positive geobotanical expression thus recorded is of such size and magnitude as to be apparent on air photographs. This is significant because geobotanical expression of ultrabasic rocks have generally been reported as 'conspicuously stunted and thinly developed', (Hawkes and Webb, 1962).

Detailed examination of plants on the pipe area also revealed effects of metal toxicities like chlorosis and white dead patches on leaves which obviously reflects higher Cr and Ni contents in soil over the pipe area in contrast to the country rock.

B4

A REVIEW OF THE KIMBERLITIC ROCKS OF WESTERN AUSTRALIA

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In the course of exploration for diamond, CRA Exploration Pty. Limited and the Ashton Joint Venture have discovered four diamond bearing kimberlite provinces in Western Australia. Three of these provinces are located marginal to the Kimberley Craton in the north of the state (Fig. 1), and one lies in the Carnarvon basin, adjacent to the Yilgarn Block, some 1300 km to the southwest.

The kimberlites intrude rocks ranging in age from Lower Proterozoic to Permian, and are covered by sequences ranging in age from Cretaceous to Miocene.

The bodies range in size from dyke-like features less than one metre in width to pipes with a surface area of 128 hectares.

The bodies with larger surface area are volcanic crater deposits, champagne-glass shaped in cross section, the narrow stem corresponding to the pipe feeder. The craters are infilled with air-fall and water-deposited tuffs and epiclastic sediments. A late-stage phase in many of the West Kimberley diatremes was the emplacement of massive, igneous-textured, magmatic kimberlite, rising to the surface in the shape of a lava-blister. This magmatic kimberlite fills the central part of the craters, and overlaps the tuffs towards the margins.

Diamond content ranges from trace amounts to economic concentrations. Feasibility studies being carried out on the Argyle AK1 kimberlite pipe are currently envisaging a 2.25 million tonnes per annum operation, to come into production in 1985, producing some 20 million carats per year, while it is hoped that limited commercial production from associated alluvial deposits will commence in the latter part of 1982.

The exploration discoveries were facilitated by early recognition that the petrography, mineralogy and chemistry of the kimberlites varies from classical types resembling those of kimberley, South Africa, to unusual more highly fractionated, alkaline, silicic varieties having affinities with leucite-lamproite and composed essentially of phenocrysts of oline ± clinopyroxene ± phlogopite + glassy groundmass. Mantle nodules recovered range from dunite to lherzolite; graphic-textured intergrowths of picroilmenite and silica (after diopside?) occur at the Skerring pipe. Heavy mineral concentrates from the kimberlites yield pyrope, picroilmenite, chrome-diopside, chromite and zircon, the former two minerals being more abundant in the classical types of kimberlite.

Recognition of the characteristics of the unusual kimberlite/lamproite association strongly influenced exploration techniques, much use being made of such minerals as chromite, andradite and zircon as kimberlite indicator minerals during heavy mineral gravel sampling.

In regions where host rocks displayed a mild magnetic response it was found that the kimberlitic bodies produces recognisable magnetic anomalies from detailed aeromagnetic surveys, and much use has been made of this technique in exploration.

B5

THE GEOLOGY OF THE MAYENG KIMBERLITE SILLS

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The Mayeng Kimberlite Sills occur in the northern Cape province of South Africa,

FIGURE 1.
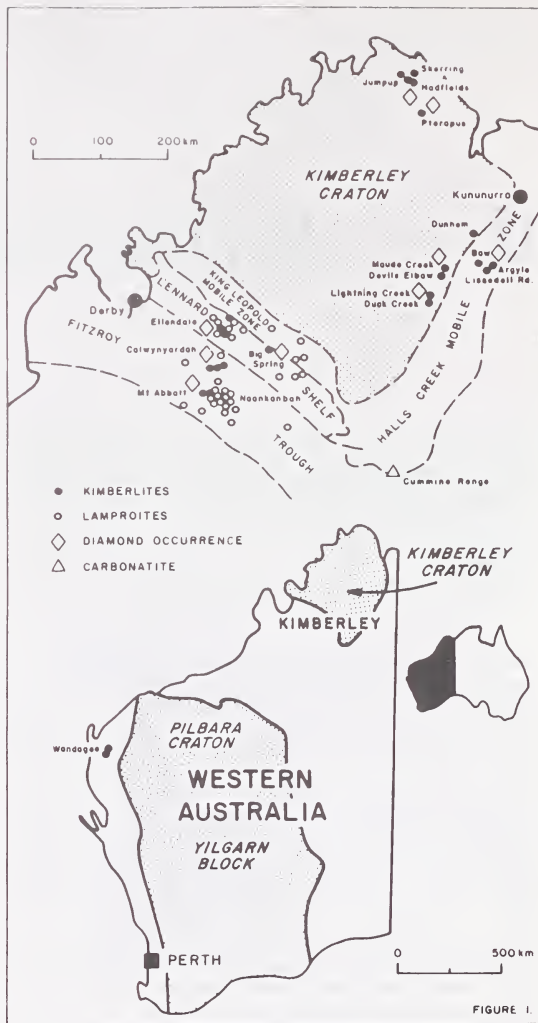
approximately 70 km north of Kimberley. The sill complex was recently discovered by DBCM prospecting personnel, in an area where previously known kimberlites occur to the north and south. These sills are intruded into a massive but jointed andesitic horizon unconformably underlying the local Ecca shales. The Mayeng sills are different to other sill complexes in the Kimberley area, where instrusion into Ecca shales is probably controlled by the overlying Kimberley Dolerite Sheet. An extensive drilling program indicated that the sill complex comprises numerous sills, apparently lensoid in shape and occurring at irregular depths. This is due to intrusion into randomly spaced planes of weakness in the jointed host lava. Detailed drilling results outlined two main sill zones, one dominantly macroporphyritic, the other aphanitic. Throughout the sill complex, however, both textural types of kimberlite are found. The petrography, mineral chemistry and bulk rock chemistries of the two main sill types have been examined in detail.

Despite the obvious differences in texture, the kimberlite sills are

mineralogically similar and classification as macroporphyritic and aphanitic-hypabyssal facies, ilmenite-rich phlogopite kimberlites would be appropriate. The mineralogical similarities of the two textural types of kimberlite are reflected in similar bulk rock compositions, although minor trace element differences are noted. In addition to a geochemical examination of the major xenocrysts, the relationships between the dominant matrix minerals have also been investigated. Of particular interest is the presence of chromian-rich ilmenite inclusions in olivine and occasionally phlogopite phenocrysts. Mantle xenoliths comprising phlogopite-ilmenite assemblages and clinopyroxene-ilmenite intergrowths are observed, though rarely. The mineral chemistry of these xenoliths has been documented and will be compared with examples from other kimberlites. From the petrographic and geochemical investigations the two textural varieties of kimberlite are apparently related, possibly through filter pressing processes and/or multiple intrusion.

B6

DIAMONDIFEROUS KIMBERLITES AT ORROROO, SOUTH AUSTRALIA

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A suite of Jurassic dykes and associated blows ranging in thickness from a few millimetres to 30 metres occur near Orroroo, South Australia. All the intrusions at surface are extensively altered but most of them are apparently petrographically similar and can be identified as altered phlogopite-rich kimberlites. Fresh material was obtained from one of the dykes at 60 metres depth. This borehole core can be classified as a hypabyssal, calcite, phlogopite kimberlite. Mineral chemistry of olivine and groundmass phlogopite, tetraferriphlogopite rims, serpentine, perovskite, spinel and clinopyroxene are characteristic of kimberlites. Whole-rock geochemistry of this dyke is also typical of such mineralogical varieties of kimberlite.

The kimberlite dykes can be divided into three main geographic groups each falling on a different, but sub-parallel, strike line. Variations in the nature of the heavy mineral concentrate and diamond content correlates with this grouping. Together with the petrography, this suggests that the dykes were intruded as three separate, but related pulses. Although no ultra-mafic xenoliths were found, the chemistry of garnets, ilmenites, diopsides and spinels is discussed.

Details of the shape and colour of the diamonds recovered from the kimberlites are given. Enstatite and magnesio-wustite occur as inclusions in the diamonds.

B7

THE PETROLOGY OF OLIVINE MELILITITES FROM NATAL, SOUTH AFRICA

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Six new occurrences of olivine melilitites have been discovered on the East Coast of South Africa. These occur as small pipes and dykes in north central Natal. They are important as they are the first recorded occurrences of alkaline ultrabasic magmatism in this area. The rocks intrude sediments of the Karoo and Cape Supergroups. The occurrences are mineralogically similar to those found on the West Coast (Moore 1979).

Petrographically both diatreme facies and hypabyssal facies textures are recognized. The diatreme facies rocks consists of varying proportions of country rock fragments, rounded 'pellets' and earlier generation fragments of olivine melilitite and phlogopite phenocrysts set in an extremely fine-grained matrix of rare clinopyroxene microlites, secondary clay minerals and cryptocrystalline carbonate. The earlier generation fragments are extensively altered but relicts of olivine, melilite, perovskite, phlogopite and small spinels can be recognized. These are set in a base of secondary clay minerals and lesser cryptocrystalline carbonate.

The hypabyssal olivine melilitites are porphyritic rocks. They consist of phenocrysts of altered olivine and minor augite, phlogopite and ilmenite in a finer grained groundmass. This consists of altered melilite, phlogopite, diopside, apatite, spinels and perovskite set in a base of serpentine and minor calcite.

These rocks are similar to kimberlites in several respect i.e. their mode of emplacement, textures and to a limited extent their mineralogy.

B8

THE 1977 EXPLOSIVE ERUPTIONS OF THE UKINREK MAARS, ALASKA

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In March/April 1977 the two small Ukinrek maars formed on the Aleutian Range when weakly under-saturated alkali olivin basalt magma rose 13 km behind the Andesite volcanic chain. During the volcanic activity eruption clouds rose to heights of up to 6500 m.

The West Maar formed within 3 days and reached a diameter of 170 m and a depth of 35 m. Its activity started with near-surface explosions leading to ejection of large partially frozen (permafrost) moraines and conglomerates and intermittant lava fountaining. After a maar forming collapse the level of explosions re-treated to deeper levels which caused ejection of blocks of the dike feeding the initial eruptions.

The East Maar formed during the following 6 days. The maar reached a diameter of 300 m and a depth of 70 m. During the eruptions frequently two styles of activity could be observed simultaneously within the maar: phreatomagmatic eruptions next to lava fountaining. Whereas the phreatomagmatic produced juvenile lapilli and bombs of relatively low vesicularity of round to cauliflower shape, as well as large amounts of wall rock fragments, the lava fountains caused formation of scoriaceous fragments.

The tuff wall therefore consists of a sequence of interlayered phreatomagmatic deposits and scoria beds.
The phreatomagmatically formed pyroclastic beds show many characteristic features observed also in the deposits of other alkali basaltic maars. Kienle, J.,Kyle, P.R., Self, S., Motyka, R.M. &Lorenz, V., 1980:Ukinrek maars, Alaska, I. April 1977 eruption sequence, petrology and tectonic setting.- J. Volcanol. Geothermal Res., 7, 11-37.

B9

EXPLOSIVE VOLCANISM OF THE WESTEIFEL VOCANIC FIELD/GERMANY

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The Quarternary volcanic field of the West Eifel is located on the presently rising Rhenish Massif above an anomalous upper mantle structure. Magmas of nephelinitic, leuzitic, basanitic, phonolitic, and tephritic composition reached the surface in about 240 volcanic structures. About 60 maars are known in this classic maar region. The remaining 180 volcanoes consist mostly of scoria cones.

Nearly all maars formed within valleys. Abundant groundwater circulating within zones of structural weakness underneath the valley floors had access to the rising magma usually during the whole period of the phreatomagmatic maar eruptions. In contrast most of the scoria cones formed on hills and valley slopes through the process of lava fountaining. Many of these scoria cones, however, erupted within small maars (initial maars). The magma rising underneath these volcanoes, therefore, must have contacted in near surface levels only limited amounts of ground water circulating in hydraulically less active zones of structural weakness. When the available water had been used up during the resulting initial maar forming phreatomagmatic eruptions the magma could rise, intrude the diatreme, and erupt on the maar floor forming a scoria cone in a second eruptive phase.

The hydrogeological situation which in the Eifel is characterized by zones of structural weekness of different hydraulic activity thus clearly controls formation of the various West Eifel volcano types: maars, scoria cones and scoria cones with initial maars.
Lorenz,V. & Büchel, G., 1980: Zur Vulkanologie der Maare und Schlackenkegel der Westeifel.- Mitt. Pollichia, 68, 29-100

B10

FRAGMENTATION OF ALKALI-BASALTIC MAGMAS AND WALL-ROCKS BY EXPLOSIVE VOLCANISM

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In the Eifel/W-Germany explosive volcanism gave rise to formation of maars. The juvenile pyroclasts of the maar deposits are typically poor in vesicle content, usually of round to cauliflower shape, and characterized by enclosed small wall-rock xenoliths.

These characteristics require intensive frag-

mentation and chilling of a vesicle poor magma, action of surface tension on the magma fragments once they had formed, and coalescence of magma fragments around wall-rock fragments which therefore became enclosed in the juvenile lapilli and bombs.

Internal concentric layering of lapilli and bombs implies liquid accretion of melt fragments around quasi-solid round juvenile clasts formed earlier.

The large proportion of wall-rock derived xenoliths in the pyroclastic deposits (up to 95 %) requires explosions which not only fragmented the magma intensively but also the wall-rocks of the explosion site. These phenomena especially the intensive fragmentation of the wall-rocks are believed to be explained by phreatomagmatic explosions only.

B11

A PROPOS DES DIATREMES ET DU PHREATOMAGMATISME : LE TERME "PEPERITE" DOIT-IL ÊTRE CONSERVÉ ?

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Les pépérites sont les roches les plus célèbres de la Limagne (Auvergne,France). Elles doivent leur nom a la présence de granules de lave vitreuse ("en grains de poivre") emballés dans une matrice habituellement marneuse. Leur genèse a fait l'objet d'une controverse qui a duré plus d'un siècle entre les partisans d'une origine volcanique sous-lacustre (Scrope,1827,1866) et ceux d'une origine intrusive, aux épontes de filons basaltiques postérieurs à la sédimentation oligocène (Dufrénoy,1830;Michel Lévy,1890). A la suite des travaux de Michel (1953) les premiers l'emportèrent et un consensus s'établit pour admettre que "les pépérites sont ( ) des roches formées par intrusion, émiettement et mélange d'une lave ( ) dans les sédiments encore plastiques des lacs du Stampien supérieur". Il s'agissait donc d'une variété de hyaloclastites - au sens originel de Rittmann - nécessairement contemporaines des lacs oligocènes. C'est cette interprétation que l'on trouve dans les traités modernes, français cu étrangers. Elle doit maintenant être définitivement abandonnée.
Les travaux clermontois récents - inédits pour la plupart - aboutissent aux résultats suivants:

dynamisme. Les pépérites sont des tufs (tufs de lapillis habituellement, plus rarement tufs cendreux) phréatomagmatiques aériens. Leur dépôt s'est fait sous forme de retombées aériennes ou de déferlantes basales. L'eau provoquant la fragmentation et la trempe du matériel volcanique et le dynamisme explosif provient des nappes aquifères, toujours présentes dans le bassin sédimentaire. La matrice "sédimentaire" est formée de "cendre" où les produits juvéniles sont subordonnés aux produits marneux. Certains niveaux sont de véritables "marnes reconstituées" où seuls les lapillis accrétionnés peuvent, macroscopiquement, attester du caractère volcanique; leur interstratification explique l'age oligocène attribué antérieurement aux pépérites.

structures. Il s'agit de diatrèmes (environ une centaine!) recoupant la totalité des couches oligocénes: les calcaires construits à Phryganes, les plus récents, se retrouvent en blocs dans les pépérites ou en panneaux descendus en bordure des structures (ex. Jussat, Hubel, etc.). Les tufs lités du remplissage ont toujours un pendage interne, donnant une disposition "en pile d'assiettes". La cheminée, bréchique, est le plus souvent centrale, mais peut se trouver aussi en bordure (Montaudou). Des dykes basaltiques tardifs peuvent recouper le diatrème, s'injecter le long de la faille bordière ou même dans l'encaissant (sill du Puy Mardoux).

appareils externes. La faible résistance des marnes à l'érosion n'a pas permis leur conservation. Par contre là dépression sommitale est préservée dans de nombreux cas: il s'agit d'un maar ou d'un cratère en entonnoir, élargi par glissement de panneaux de l'anneau de tufs ou de l'encaissant sédimentaire pour les plus grandes structures (Gergovie). Cette dépression est remplie de sédiments détritiques, chimiques ou organiques, et/ou de produits volcaniques banals (lac de lave ou cône de scories); grâce à l'inversion de relief, ces remplissages forment l'essentiel des reliefs de la Limagne de Clermont et de la Comté d'Auvergne.

âge des pépérites. Toutes les structures pépéritiques actuellement datées paléontolcgiquement ou géochronologiquement sont miocènes. D'autres pourraient être plus jeunes, mais aucune ne semble pouvoir, géologiquement, être oligocène.

conclusion. Génétiquement, les pépérites sont des tufs lités ou massifs comparables à beaucoup d'autres tufs résultant d'une activité phréatomagmatique. Leur originalité vient du mélange intime des petits granules basaltiques et de la matrice cendreuse d'origine sédimentaire, qui donne à la roche un cachet particulier. C'est la nature des roches traversées (marnes) et la profondeur des nappes aquifères en Limagne qui a permis un brassage aussi efficace dans les systèmes fluidifiés à l'origine de ce volcanisme.
Nous proposons de conserver le terme "pépérite" comme un terme de faciès.

B12

PHREATOMAGMATIC ACTIVITY IN THE VOLCANISM OF THE FRENCH MASSIF CENTRAL

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Phreatomagmatism is an essential feature in the tertiary and quaternary volcanism of central and south-eastern France: (i) the oldest volcano (Menat group, 60 M.y.) and the youngest (lac Pavin, 3450 B.P.) are maar-type vents; (ii) the northernmost (Menat group) and the southernmost (Agde volcano) are also maar-type vents; (iii) maars belong to the basic magma-type as well as the intermediate or differentiated magma type. Phreatomagmatic structures prevail (or are exclusive) in paleolacustrine surroundings: Bassin du Puy and Cantal, and in sedimentary areas: Limagne, Coirons, Causses, Lodevois, Escandorgue. They are common in the plateau-basalts fields where underground water is abundant (Devès, Cézallier, Aubrac), and in the strato-volcanoes (Cantal). They are less frequent (about 10% of the vents) in the areas characterised by volcanoes scattered on a granitic basement (Chaîne des Puys). In the Livradois country it has been pointed out that the presence of a sedimentary layer (at the time of eruption, but now eroded) at the surface of the granitic basement explains the frequency of the phreatomagmatic volcanoes.

All the characteristic features of interest concerning phreatomagmatism can be observed, except the deep roots of the volcanoes:
-The phreatomagmatic structures are maars, or tuff-rings, and their underlying diatremes; the present morphology depends on the hardness of the wall rocks, the age of the volcano, the presence (or the lack) of a cap of hard rocks (cooled lava lake or various sediments) in the paleocrater. The level of erosion is never very deep, usually less than several tens of metres, though exceptionally a hundred metres or more. In exceptional cases it is possible to observe in a single volcano (Langeac, H.L., Rochessauve, Coirons) a crater with associated deposits and the upper part of the underlying diatreme.
-Many outcrops are favourable to the study of eruptive mechanisms (base surge, flow or fall deposits) and subsequent phenomena in the pipe (fluidization, collapse).
-Various types of infilling of the crater are also interesting; this can be volcanic, both autochtonous (strombolian cone, pillow lavas, lava lake, dome or protrusion), and allochtonous (lava or pumice flow) or sedimentary: limestones, chemical clays or silica, such as diatomite, resinite or millstone deposits.
-The sedimentary filling of a maar crater is always fossil-rich, with pollens, leaves, fishes, etc. It has been pointed out that the vertebrate beds found in the volcanic areas of the french Massif Central are generally in maars or tuff-ring craters.
-The example of the Chaîne des Puys shows that differentiated magmas are strongly affected by even a minimal water supply; basaltic magmas need larger quantities of water to modify their activity.
Our works have pointed out:
-(i) that sub-aquatic (sub-marine, sub-lacustrine or sub-glacial) activity "surtseyan type" is very different from subaerial activity "phreatomagmatic s.s. activity";
-(ii) that the magma type is an important factor in the power supply, conditioning subaerial activity: as a general rule maars result from basaltic magmas (sometimes from differentiated magmas) and tuff-rings from differentiated magmas;
-(iii) that the substratum is also important, from the point of view of its structure (which affects the water supply), its texture (which affects the dust supply, which will condition fluidization), and its superficial morphology (which conditions the path of the base surge or flows).

B13

HYALOCLASTITES DANS LES LACS VILLAFRANCHIENS DU VELAY (France)

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Les fossés d'effondrement villafranchiens du Velay ont été le siège d'une sédimention lacustre avec laquelle interfèrent des structures hyaloclastiques de nature basanitique. La montée de ces magmas est liée aux distensions responsables de la subsidence.

Les structures observées dans le Velay (Bassins du Puy et de Langeac en particulier) varient selon les niveaux d'érosion : écoulements pyroclastiques et anneaux de tufs (formes tabulaires), diatrêmes à tufs lités centroclinaux (buttes et collines), pipes bréchiques armés de dykes (rochers et aiguilles). Des phénomènes de subsidence intracratérique ont pu être observés (panneaux de substratum ou de l'anneau de tufs basculés). Ces formations bréchiques, litées ou non, se présentent sous la forme de granules vitreux emballés dans un ciment cendreux induré.

L'observation d'éruptions récentes en milieu aquatique (Capelinhos aux Açores, Surtsey en Islande) a permis l'étude de dépôts de hyaloclastites et leur évolution ultérieure. Au Capelinhos en particulier, la consolidation des niveaux cendreux par palagonitisation a pu s'effectuer pendant l'éruption et transformer sur place la base immergée de l'anneau de tufs. L'influence de l'eau disparaissant, l'activité évolue vers un modèle plus banal, strombolien ou (et) effusif dont les produits comblent alors l'ancien cratère de l'anneau de tufs.

La convergence des formes, structures et produits de ces appareils marins avec ceux du Velay est remarquable, impliquant nécessairement des conditions génétiques voisines, donc des éruptions en eau libre (lacs villafranchiens) pour les appareils bréchiques vellaves. Ces derniers ont en outre l'avantage, compte tenu de leur niveau d'érosion, de permettre l'accès aux substructures indispensables à la compréhension des mécanismes éruptifs.

Peter Nixon, Adolphe Nicolas, Jean-Claude Mercier and others during Navajo field trip.
Photo C. Froidevaux

C   Kimberlites: how? why?

C1

MINERALOGICAL AND TEXTURAL-GENETIC CLASSIFICATION OF KIMBERLITES IN NORTHERN COLORADO AND SOUTHERN WYOMING, U.S.A.

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Accurate comparisons between kimberlites from different world-wide localities commonly are difficult to establish from the literature because no unified scheme of classification has been utilized. Mineralogical and textural-genetic classifications recently were developed by Skinner and Clement (1979) and Clement and Skinner (1979) in an effort to correct previous deficiencies in nomenclature. These classifications have been combined into a descriptive terminology scheme that is being applied to North American kimberlites (McCallum, 1981). Most Colorado-Wyoming kimberlites are phlogopite, calcite, serpentine, varieties, but opaque mineral, diopside, or perovskite rich types are abundant at some localities. Carbonatized kimberlite is common and silicified phases occur locally. All varieties are classified as diatreme and hypabyssal facies, any crater facies having been removed by erosion. Diatreme facies consist of tuffisitic kimberlite and tuffisitic kimberlite breccia with microlitic, and crystallinoclastic and segregationary textures. Autolithic types are abundant in some pipes and commonly reflect substantial compositional differences from host phases. Hypabyssal facies include both aphanitic and microporphyritic kimberlite and kimberlite breccia. Segregationary textures are common, and a pronounced flow layering is present locally. Wall rock breccia containing minor amounts of kimberlitic components occurs adjacent to several pipes and is characteristic of the hypabyssal or "root zone" facies. Names of specific kimberlite phases are established primarily on texture, and dominant matrix minerals are included as modifiers (e.g. tuffisitic calcite kimberlite breccia). (Study supported, in part, by Earth Sciences Section of NSF, Contract EAR-7810775)

C2

KIMBERLITE TEXTURES I

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The occurrence of hypabyssal- and diatreme-facies kimberlites in kimberlite pipes has long been recognized. In this contribution, the first of two companion papers, the range of textures exhibited by hypabyssal-facies kimberlites is described and the origins of the different textures are evaluated.

Particular attention is paid to the genesis of a variety of segregationary textures. The irregular to globular segregations in these rocks are commonly composed of the volatile-rich, late-crystallizing components of the kimberlites but relatively high temperature, anhydrous minerals also occasionally occur in segregations. Volatile-rich segregations are ascribed to a variety of causes; some are interpreted as segregation vesicles (gas cavities filled by residual liquids) and others are regarded as direct segregations of melt. Most are, however, ascribed to condensation of gas-rich exsolved volatiles following varying degrees of vesiculation under conditions where the escape of the exsolved fractions was inhibited. The possibility that some segregations may relate to carbonate-silicate or silicate liquid immiscibility is examined.

The textures of rocks which are intermediate in character between hypabyssal- and diatreme-facies kimberlites are also described and their modes of origin assessed.

C3

KIMBERLITE TEXTURES II

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In this contribution, the second of two companion papers, the range of textures exhibited by diatreme-facies kimberlites is described and their petrogenesis is discussed.

Emphasis is placed on the pelletal textures which are characteristic of many tuffisitic kimberlite breccias. These textures reflect the occurrence of abundant pelletal lapilli which display a variety of internal and morphological features. Variations in the character of lapilli are evaluated in terms of an evolutionary scheme which incorporates an assessment of the degrees to which lapilli are formed prior to, or during, vapour-solid fluidization events which were triggered by explosive breakthrough to surface. Modifications of the lapilli by deuteric alteration or

post-fluidization crystallization, under stagnant conditions, are described. The formation of segregationary and uniform textures by post-fluidization crystallization of vapour condensates are also considered.

Some attention is paid to the effects of fluidization (and contemporaneous contamination of residual fluids during fluidization) on the mineralogy of diatreme-facies kimberlites.

C4

A NEW LOOK AT PRAIRIE CREEK, ARKANSAS

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Previous studies of the Prairie Creek occurrence have identified three main rock types namely; "volcanic breccias", "tuffs and fine-grained breccias" and hypabyssal kimberlite or peridotite. We take a new look at these rocks in the light of a suggestion by R.H. Mitchell (pers. comm.) that the body is not a true kimberlite but rather a lamproite.

Our investigation confirms the presence of three distinct rock groups which include both hypabyssal and crater-facies types. The so-called "volcanic breccia" and "tuffs" are both considered to be predominantly of pyroclastic origin. The "volcanic breccias" are subdivided into two sub-groups. One, composed of igneous lapilli set in a serpentinous base, is interpreted as a primary tuff. The other is thought to be a reworked tuff. The latter group is similar in many respects to the so-called "tuffs". These contain abundant comminuted and xenolithic material in addition to igneous lapilli. Certain features of these rocks are atypical of kimberlites.

The hypabyssal rocks contain two generations of relatively abundant olivine (Fo$_{88-93}$) in a fine-grained matrix composed of phlogopite, clinopyroxene, amphibole, perovskite, spinel and serpentine. Some phlogopite and serpentine crystallised from a glass. Although many petrographic features of these rocks are similar to those of kimberlites, the form of the euhedral olivine, presence of abundant glass and occurrence of potassic richterite are uncharacteristic of kimberlite but typical of lamproitic rocks. Both the groundmass phlogopite (4-5 wt.% TiO$_2$) and the bulk rock have compositions intermediate between lamproite and kimberlite.

It is concluded that the Prairie Creek intrusion is transitional between kimberlite and lamproite.

C5

POSSIBLE PRE-KIMBERLITE SERPENTINIZATION IN ULTRABASIC XENOLITHS FROM BULTFONTEIN AND JAGERSFONTEIN MINES, SOUTH AFRICA

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Textural analyses of garnet peridotites showing various degrees of deformation revealed an early generation of pre- and synkinematic serpentine that appears to predate kimberlite emplacement. In sheared nodules, serpentine fibers between recrystallized olivine and in fractured

porphyroclasts and layers of orthopyroxene are consistently parallel with the planar fabric. Numerous porphyroclastic nodules have sets of serpentine-filled fractures perpendicular to the mineral elongation. In some porphyroclastic nodules random networks of serpentine-filled fractures are deformed near orthopyroxene and garnet porphyroclasts. Sections of xenolith-kimberlite contacts show that deformation-related fibrous serpentine veins may have been reopened and filled by a late generation of nonfibrous serpentine.
   Time relationships between early serpentinization and K-metasomatism at Bultfontein are difficult to establish, though rare textures suggest that richterite may have overgrown olivine with serpentine-filled fractures. As some of the K-metasomatism is also synkimmatic, it is possible that the two are related. Recognition of a pre-kimberlite serpentinization overprint on anhydrous assemblages of diverse P-T conditions at Jagersfontein casts doubt on the interpretation that the two rock types were incorporated into the kimberlite at different depths. It raises the possibility that rocks originally equilibrated at different P and T became tectonically juxtaposed prior or during serpentinization preceding incorporation into the kimberlite.

C6

THE KOIDU KIMBERLITE COMPLEX, Sierra Leone.

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Three Kimberlite pipes, multiple dikes, and a small ring-dike complex of kimberlite occur in the Yengema-Koidu area. Dikes are both older and younger than the kimberlite pipes and a variety of textural, petrological, and mineralogical types characterize the complex. Discrete ilmenite nodules show evidence of coupled exsolution (ilm$_{ss}$ from geik$_{ss}$) and subsolidus reduction (sp$_{ss}$ from ilm$_{ss}$) associated with Cpy + Po+Pn. These ilmenites have 3-6 wt. MgO and 0.2-1.4 wt Cr$_2$O$_3$. Redox reactions producing Mn-rich ilmenites (up to 16 MnO) and spinels (up to 1.2 wt MnO) are intimately associated with calcite. Ilmenites in ilm-pyroxene intergrowths contain 10-12 wt MgO and 0.8-1.5 wt Cr$_2$O$_3$, and are associated with Jd pyroxene, sulfides, and trapped magmatic inclusions. Both diamond-bearing and non-diamond bearing eclogites are present, and metallic Fe has been identified in one eclogite. Discrete chlorite nodules (up to 5cm in size) and primary groundmass chlorite are highly oxidized (8-20 wt $_2$O$_3$, low in Al$_2$O$_3$ (9-10 wt.), and high in MgO (21-28 wt) Phylogopites low in Cr$_2$O$_3$ (0.05 wt), TiO$_2$ (0.20 wt) and high in FeO (7-8 wt) have reversed pleochroism, and are mantled by normal pleochroic phlogopites high in Cr$_2$O$_3$ (1.5 wt), TiO$_2$ (2-3 wt). and low in FeO (4-5 wt). Core phlogopites are preferentially replaced by chlorite. Bulk chemistry of dike and pipe kimberlites are markedly different in the ranges of composition:the former are tightly clustered (e.g. MgO= 26-32 wt CaO= 3-8 wt., Al$_2$O$_3$= 2-4 wt) whereas the latter are heterogeneous (e.g. MgO= 16-30 wt, CaO= 2-18 wt, Al$_2$O$_3$= 2-9 wt). Volatile variations (CO$_2$ and H$_2$O) suggest that the earliest kimberlite magma (i.e. autolith) was H$_2$O enriched, that the later kimberlite was CO$_2$ enriched (i.e. autolith encasement) and that the host kimberlite (i.e. youngest) was intermediate. Preliminary paleomagnetic studies record paleovector directions

consistent with a Jurassic age of diatreme emplacement.

C7

CARBONATE TUFF FROM MELKFONTEIN, EAST GRIQUALAND, SOUTH AFRICA

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The Melkfontein carbonate tuff overlies the southern slopes of a ridge of Beaufort sandstone that is cut by Karro dolerite intrusions. The tuff is considered a remnant of a volcano and is believed to have erupted at a relatively recent age (63 M.Y.), in comparison to the nearby kimberlitic intrusions.

The carbonate tuff is composed of calcite that encloses numerous xenocrysts of garnet, clinopyroxene, amphibole, mica, and plagioclase together with "cognate" magnetite, apatite, and zircon crystals. Garnet is iron-rich ($Mg/Mg + Fe^{+2}$ 0.40 - 0.54, TiO_2 0.04 - 0.2 wt %, Cr_2O_3 0.01 - 0.07 wt%). Clinopyroxene ($Mg/Mg + Fe^{+2}$ 0.45 - 0.68, $Ca/Ca + Mg$ 0.54 - 0.57) is sodic, containing 3.0 to 6.5 wt % Na_2O. Alkali amphibole (Na_2O 4.0 - 4.5, K_2O 1.2 - 1.4, TiO_2 1.2 - 1.7 wt %) occurs as discrete xenocrysts or as rims on clinopyroxene. Biotite is iron-rich ($Mg/Mg + Fe^{+2}$ 0.51 - 0.62) and contains 1.5 to 2.4 wt % TiO_2. Plagioclase occurs as discrete xenocrysts of albite ($Ab_{98.1}An_{0.9}Or_{1.0}$) or as crystals of andesine ($Ab_{70.2}An_{27.5}Or_{2.3}$) attached to large garnet xenocrysts. The mineral chemistry of clinopyroxene, garnet, amphibole, and mica in the Melkfontein tuff is different from that reported for these minerals in carbonatites (or kimberlites). It is similar, however, to the mineral chemistry reported for these minerals in garnet granulite xenoliths from Lesotho kimberlites (Griffin et al., 1979). Such similarity suggests that they are derived by disaggregation of garnet granulite xenoliths from the lower crust at Melkfontein. The occurrence of "cognate" magnetite (1.7 - 8.6 wt % MgO, 1.4 - 7.8 wt % TiO_2, <0.01 wt % Cr_2O_3), apatite, and zircon in the Melkfontein tuff suggests some similarity to carbonatites.

C8

THE OPAQUE OXIDES OF THE WESSELTON MINE KIMBERLITE, KIMBERLEY, SOUTH AFRICA.

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The Wesselton Mine is one of four operating diamond mines in Kimberley, South Africa. It yields approximately 330000 carats of diamonds a year. The Wesselton kimberlite pipe has had a complex geological history and excluding minor dykes and sills, 9 or possibly 10 different kimberlite intrusions have been recognised between the 435 and 1020 metre levels. In addition two major areas of contact breccias occur below the 660 metre level (Clement pers. comm.).

The kimberlites have been examined petrographically with particular emphasis on the opaque minerals in the groundmass. These minerals are spinels, ilmenite, perovskite and rutile. Representative microprobe analyses of these minerals have been obtained.

Subhedral to euhedral groundmass spinels in the Wesselton mine kimberlites range in size from 0,002mm to 0,1mm but are usually 0,04mm. They exhibit a normal magmatic trend and evolve from low TiO_2, high Cr_2O_3 cores (picrochromites) to low Cr_2O_3, high TiO_2 and Fe_2O_3 rims (titanomagnetite). Despite some chemical overlap, spinels from different kimberlite intrusions can be distinguished from one another. The Wesselton spinels do not show a zonation trend from titanomagnetite cores to magnesium pleonaste rims similar to that described for the De Beers kimberlite by Pasteris (1980).

Ilmenite xenocrysts and primary groundmass ilmenites in the Wesselton kimberlites are characterised by high MgO and Cr_2O_3 contents, the highest MgO contents occuring in the groundmass ilmenites. Both varieties of ilmenite display reverse zonation with rims more magnesium than cores.

C9

MAGMA MIXING IN THE EVOLUTION OF KIMBERLITE: COMPOSITIONALLY DISTINCT MEGACRYST SUITES FROM S.W. PENNSYLVANIA, USA.

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Megacryst populations recording a fractionation interval within kimberlitic melts have been documented from many occurrences; a locality in Pennsylvania records a magma-mixing event involving a fractionated melt and a less evolved, perhaps parental, melt. Furthermore, there is complete documentation of the subsequent evolution of the hybrid melt to its final crystallization.

Two compositionally distinct populations of megacrysts and phenocrysts occur: (1) a primitive suite composed of Cr-garnet and olivine (Fo 92-90), the latter containing inclusions of Cr-garnet, Cr-diopside, enstatite, and immiscible sulphide blebs; and (2) a more evolved suite consisting of Cr-poor garnet, olivine (Fo 85-83), and megacrysts and inclusions of picroilmenite. The two populations are compositionally similar to different stages of the fractionation sequence of kimberlites possessing a continuum of megacryst compositions (e.g., the Monastery kimberlite), particularly with regard to the compositions of co-precipitating Cr-poor garnet and picroilmenite. Reverse Mg-zonation in ilmenite megacryst rims and zonation in all olivine rims to an equilibrium composition of Fo 88 provide tangible evidence for mixing of the two populations and their host melts. Ilmenite, identical in composition to that in the re-equilibrated megacryst rims, was a liquidus phase in the hybrid melt, followed paragenetically by Cr-spinel, then Ti-magnetite; Cr-, Ti-phlogopite, zoned to Ti-phlogopite is the dominant mafic silicate phase.

P-T calculations on garnet lherzolite xenoliths indicate formation of the kimberlitic melt at 53-55 kb and 1320-1350°C; values from the megacrysts indicate that the mixing took place at lower temperatures (1170-1200°C).

Mixing calculations verify the mineral evolutions observed and have allowed an assessment of the relative proportions of the melts involved in the mixing.

C10

LES ROCHES ULTRAPOTASSIQUES (LAMPROITES) DE LA REGION VOLCANIQUE NEOGENE DU SUD-EST DE L'ESPAGNE

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Dans la région volcanique néogene du Sud-Est de l'Espagne, se trouvent associées espatial et temporellement des roches calco-alcalines, shoshonitiques et ultrapotassiques.

Les lamproites se présentent en pipes de diametre reduit (~ 1 km) et exceptionellement comme des laves. Essentiellement, elles sont constituées par de l'olivine (Fo_{92}-Fo_{78}), de la phlogopite, du clinopyroxene ($En_{51}Fs_4Wo_{45}$-$En_{46}Fs_{13}Wo_{41}$) et des proportions variables, selon le degré de cristallinité, de la richterite potassique, de la sanidine et du verre; dans quelques types, des orthopyroxenes ($En_{85}Fs_{12}Wo_3$-$En_{72}Fs_{25}Wo_3$) et de la leucite peuvent apparaître. Sur la base des compositions normatives, on peut distinguer quatre types de lamproites: jumillites (avec ol et lc normatives), cancalites (avec ol normative), fortunites (avec $< 5\%$ de ol ou q normatives) et verites (avec > 5 de q normative). Tous ces types montrent une haute relation $Mg/Mg+Fe^{2+}$ (0,82-0,72), des hauts contenus en Ni,Cr,K_2O,P_2O_5,Ba,Sr,Th et Zr, et un bas teneur en Al_2O_3 et CaO.

Les particularités de ces roches ne peuvent-pas s'expliquer par de simples processus de cristallisation fractionnée a partir d'un magma commun, et non-plus par la variable fusion partielle d'un manteau péridotitique standard. Par contre, quelques données mineralogiques et chimiques son favorables au mélange des magmas de differente composition. Les calculs effectués à ce sujet avec les élements majeurs, indiquent que les quatre types de lamproites du Sud-Est de l'Espagne pourraient avoir été originés par le mélange,dans des proportions variables, d'un magma shoshonitique et d'un autre de type kimberlitique.

C11

THE ULTRAPOTASSIC ROCKS OF THE BETIC CORDILLERA, SPAIN

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The ultrapotassic rocks of SE Spain are re-investigated mainly on the basis of new geo-chemical and mineralogical data.The rocks are characterized by phlogopite,olivine,sanidine, +biotite,+clinopyroxene,+orthopyroxene,+ K-rich amphibole,+glass.Phlogopite is present both as phenocrysts and as microcrysts(Ph1 and Ph2): Ph2 has Ti and Fe/Mg higher than Ph1. Only in some case the chemistry of phlogopite is related to the degree of fractional crystallization. Four different kinds of biotite have been found. lowTi-biotite associated with crustal xenoliths unstable biotite(B1), phenocrysts(B2),microcrysts(B3).Sometimes Ph and B coexist together. The rocks have low – moderate Al_2O_3(8.9-12.8), low Fe/mg ratio, Nb/Y =1,high contents of Zr,P, Th,Ce,Ba,Ni,Cr, and low Sc and Y values. Many rocks exhibit(Na+K)/Al(atoms) major than unit. Frequently the investigated outcrops are geochemically well identified. Nevertheless,chemical variations between the different outcrops are gradual. The petrogenesis of these rocks is really difficul to explain.The magmas generated in the mantle, but crustal contamination or magma mixing largely influenced the rock chemistry. The fluids too possibly played an important role during the petrogenesis and produced selective enrichment of several elements.

C12

TRACE ELEMENT GEOCHEMISTRY OF K-RICH LAVAS FROM ALBAN HILLS, ROMAN COMAGMATIC PROVINCE (Italy)

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Quaternary K-rich volcanics are widespread in the Roman-Neapolitan area.Based on major and trace element abundances a potassium series(KS) and a high-potassium series (HKS) have been distinguished. KS rocks are represented by alkali basalts, trachybasalts, latites and trachytes which have lower enrichment in K and other incompatible elements with respect to leucitites, leucite-tephrites and leucite -phonolites which make up the HKS. At Alban Hills together with predominant pyroclastics, leucititic and tephritic leucititic lava flows occur. On 22 selected Alban lava samples major element, Cs,Rb,Sr,Hf,Ta,Th,Sc,Cr,Co,Ni and REE contents have been determined.SiO_2 ranges between40-49%,K_2O 5-10% ca,Mg_v=37-69. Cs(4.8-61ppm),Rb(47-540ppm),Sr (1090-2700ppm),Th(36-130ppm) and LREE display all high values.REE patterns are strongly fractionated for both light and heavy REE with a significant negative Eu anomaly.The ferromagnesian elements are variable and,except for Co, positively correlated with Mg_v.The obtained data indicate that the K-rich volcanism of Alban Hills is the product of low degree of melting of a LILE-enriched garnet -peridotitic mantle.The observed elemental variations have been produced by low-pressure fractionation with separation of cpx,leucite and spine l as main phases.The distribution patterns of Alban Hills lavas normalized against a primordial mantle composition are similar to those observed in leucite-bearing volcanics from Aeolian arc, where these rocks are associated with shoshonitic volcanics and both follow calc-alkaline magmatism.This supports the view that the K-rich magmatism of Roman comagmatic province represents the latest stage of a subduction-related volcanic cycle.

C13

KIMBERLITE AND LAMPROITE DYKES, WEST GREENLAND. IMPLICATIONS FOR MELTING OF RICHTERITE, PHLOGOPITE AND CLINOPYROXENE IN A LIL ENRICHED MANTLE.

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Thin kimberlite and lamproite dykes are exposed in the Precambrian rocks of the Sissimiut area, central West Greenland. The dykes are remarkable fresh and show evidence of multible intrusions. The kimberlites are characterised by olivine megacrysts with groundmass perovskite and spinel, and contains olivine-phlogopite-ilmenite nodules. Two types of lamproites have been distinguished. The most common type is pseudoleucited ,rutile-, +/- olivine-bearing. The second is a MARID type with richterite, rutile, Mn-ilmenite, and megacrysts of clinopyroxene.

Geochemically the kimberlites are distinguished from the lamproites by higher MgO,FeO,CaO, CO_2,Cr,Ni,Co and Cu contents, and lower amounts

of SiO_2, TiO_2, Al_2O_3, Na_2O, K_2O, P_2O_5 and incompatible trace elements.

The geochemical evolution have been investigated by molecular ratio diagrams with Zr as the ratio element in order to eliminate deformation of the data by the closure effect.

The kimberlites and lamproites have differing trends, and one rock type cannot have evolved from the other. The geochemical variation of the lamproites modelled with congruent melting of known mantle phases give rich/phl/cpx/ap/ru = 30/45/20/3/2. This solution yields too high (Fe,Mg)O values and too low alkali content. A model is proposed where incongruent melting of phlogopite to a melt of sanidine-ilmenite composition leaves a residue of olivine. This model gives rich/phl/cpx/san/ap/ilm = 38/27/11/16/3/5. The kimberlite variation can be explained by melting of ol/phl/cc/cpx/spi/ap = 65/17/9/5/3/1.

REE distributions of both rock types indicates that the mantle source was heavily enriched in REE and especially the LREE.

C14

PETROGRAPHY, GEOCHEMISTRY AND Sr ISOTOPIC COMPOSITION OF THE MBUJI-MAYI AND KUNDULUNGU KIMBERLITES (ZAÏRE).

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At Mbuji-Mayi the diamond-rich kimberlite breccia, of late Cretaceous age, contains nodules of "primary kimberlite". Phenocryst phases are Cr-chlorite (often rimmed or replaced by phlogopite) and two generations of olivine completely pseudomorphosed to phlogopite and calcite. The very fine-grained matrix consists of Cr-chlorite, hydromica and calcite with minor amounts of apatite, magnetite and rutile. The phenocryst assemblage and mineral transformations are rather peculiar. Given the absence of phlogopite phenocrysts, one cannot rule out the possibility that these kimberlites were originally of basaltic type.

Except for a higher carbonate content, they are chemically similar to South-African kimberlites. The $^{87}Sr/^{86}Sr$ initial ratios are low (0.7040-0.7045) which point to a mantle origin without crustal contamination. The isotopic ratio in rare carbonate inclusions is equally low suggesting that they are genetically linked to the kimberlites. REE patterns are the same as those observed in South-African kimberlites : $(La/Yb)_N \approx 100$; $La_N = 100-600$; no Eu anomaly. Cr-rich diopside megacryst have lower $^{87}Sr/^{86}Sr$ ratios (ca. 0.7030) implying a xenolithic character. The pronounced HREE depletion seems to indicate that they formed in equilibrium with garnet.

The Kundulungu kimberlites are of the basaltic type (fresh olivine phenocrysts, fine-grained chloritic matrix, absence of phlogopite phenocrysts). They are much lower in carbonates but, in terms of trace element and Sr isotopic geochemistry they are very similar to the Mbuji-Mayi and other kimberlites.

C15

Nd AND Sr ISOTOPIC COMPOSITIONS AND REE GEOCHEMISTRY OF ALKALI BASALTS FROM THE MASSIF CENTRAL, FRANCE.

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Cenozoic volcanic rocks of alkali basalt family are widespread in the Massif Central. They are underlain by the Hercynian granitic basement. The compositions of basalts range from hawaiitic to basanitic, but basanites dominate the rock types. Results show that the basalts from the Cantal, the Aubrac and the Mont Dore (T< 10 m.y.) have 143 Nd/ 144 Nd = 0.51283 to 0.51299 or ϵ_{Nd} = +3.7 to +6.7, and 87 Sr/ 86 Sr = 0.70338 to 0.70435. Quaternary basalts from the Chaîne des Puys yield 87 Sr/ 86 Sr = 0.70366 to 0.70458. In a Nd-Sr isotopic correlation diagram, these data fall within the correlation band. The positive ϵ_{Nd} values suggest that their magma sources have had a time-integrated LREE depletion, similar to that observed for the MORB sources.

The REE data show typical LREE enrichment of alkali basalts, with La_N = 80-250 X, Lu_N = 7-13 X, $(La/Yb)_N$ = 10-20, and practically no Eu anomalies. Geochemical arguments do not favor any significant crustal contamination for the derivation of these basalts studied. Theoritical considerations call for a recent mantle metasomatism in which a LREE depleted source region was enriched in LREE and other LIL elements before partial melting events. Since the positive ϵ_{Nd} values and enriched LREE abundances are so common to most alkali basalts and related rocks, it appears that mantle metasomatism is precursory to the generation of alkali basalts and that the influx of metasomatic fluids have localized the melting events.

C16

Sr, Nd ISOTOPES AND TRACE ELEMENT GEOCHEMISTRY OF MELILITITES FROM WESTERN EUROPE

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Melilitite bearing nephelinites (melilitites) are commonly found in provinces where evidence of melting at deep levels in the mantle (kimberlites, carbonatites) exists. They are actually among the most mafic basaltic rocks and their high content in REE and Sr together with a fairly rapid eruption mode would suggest little contribution of high level contamination in their genesis.

Twenty cenozoic melilitites from Europe (Spain, France, W. Germany and Czekoslovakia) have been analysed for Sr, Nd isotopic composition and trace element (REE + transition elements) contents. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios plot mostly within and partly below the oceanic trend with no obvious regional variation. The average $^{87}Sr/^{86}Sr$ ratio is 0.703776 (range 0.70322-0.70446), the average $^{143}Nd/^{144}Nd$ ratio of 0.512832 (0.51269-0.51300). Leaching experiments show isotopic inhomogeneities and suggest the present of a high $^{87}Sr/^{86}Sr$ component interpreted as being of crustal origin. The origin of melilitite could be found in an ordinary (oceanic type) upper mantle of which the melting products experienced contamination at high level during upward migration of the magma in the crust. The Sr/Nd ratio of the contaminant is tentatively estimated to fall in the range 3 to 15 which could fit upper crustal rocks such as shales or granites.

REE elements present the usual pattern of alkali-rocks with high concentration level, high Ce/Yb ratios (58 to 130) and no Eu anomaly.

Beside additions evidence for crustal contamination, REE and tran-

sition elements may carry information on the origin of the magmas. If melting of a recently metasomatized mantle could provide a satisfactory interpretation, wall rock alteration formalized with the zone refining equation fit well the present data. An important implication of this process is the rapid equilibration of high partition coefficient elements (HRE for instance) with conduit walls in contrast with low partition coefficient elements (LRE). It is found that a liquid generated in the garnet stability field of the mantle and rising through spinel lherzolites or harzburgites would result in magmas having geochemical characteristics similar to melilitites or kimberlites.

C17

Nd ISOTOPES IN KIMBERLITES AND MANTLE EVOLUTION

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Estimation of P, T, conditions of equilibration of garnet peridotite xenoliths in kimberlites indicates that kimberlitic liquids are derived from depths greater than 180 kms. No other rock, with a depth of origin greater than 180 kms, is readily available for analysis. A Nd-isotopic study of kimberlites of different ages from different continents is, therefore, important in understanding the history and evolution of the mantle. The present study is an extension of our earlier study (Basu and Tatsumoto, 1978, 1979, 1980) where we demonstrated that kimberlites are derived from a relatively undifferentiated chondritic mantle.

We have analyzed the Nd-isotopic composition of the following kimberlites and related rocks: Nine kimberlite pipes from South Africa and Lesotho; two from southern India; one from the U.S.S.R.; fifteen kimberlite pipes and related dike rocks from eastern and central U.S. and three pipes from the Shangdong Province of eastern China. The age of emplacement of these pipes ranges from 1300 m.y. to 90 m.y. before present. The initial Nd-isotopic compositions of these kimberlitic rocks expressed as ε_{Nd}^{I} with respect to a chondritic bulk earth growth curve show a range between 0 to +4, with the majority of the kimberlites being in the range 0 to +2. This result strengthens our earlier conclusions that kimberlitic liquids are derived from a relatively primeval and unique mantle reservoir with a nearly chondritic Sm/Nd ratio.

C18

THE EVOLUTION OF OLIVINE MELILITITE AND KIMBERLITE MAGMAS

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Olivine melilitites and olivine nephelinites occur in two pipe clusters in the Namaqualand-Bushmanland area of western South Africa. Disparate ages and differences in initial Sr-isotope ratios indicate that it is not possible to relate these rocks to a common parental magma. Nevertheless, it is possible to model the differences in bulk rock chemistry between the pipes in terms of processes common to magmas generated in the same tectonic environment, although it is recognised that the rocks themselves cannot be comagmatic.

Chemical characteristics of the southern (Garies) pipes lower MgO and higher concentrations of some incompatible elements indicates that they are compositionally more "evolved" than those in the Gamoep pipe cluster to the north. Compositional variation withinthe southern pipe cluster has been dominated by fractional crystallisation of olivine, melilite, perovskite and titanomagnetite (the low pressure phase assemblage in these rocks).

Compositional variation within the northen pipe cluster reflects the imprint of polybaric fractional crystallisation which has involved both a

high pressure (megacryst) phase assemblage of olivine, clinopyroxene and ilmenite and the same low-pressure phases that dominantly control the compositional variation in the southern pipes.

Substraction of the high-pressure phases from an average Gamoep (northern magma composition will produce a composition similar in "compatible" major element contents to that of an average Garies (southern) magma. This suggests that the Garies pipes could have been derived by high-pressure crystal fractionation of a more primitive magma which was similar in major element chemistry to an average Gamoep composition. However, the enrichment of incompatible trace elements such as Zr and Nb in the Garies rocks relative to those in the Gamoep pipes is far higher than would be predicted by a simple crystal fractionation model. This suggests that the primary magmas for the two pipe clusters were produced by different degrees of partial melting or that there were compositional differences between their respective source areas.

Although it is possible to model the compositional derivation of the Garies rocks from a Gamoep-type magma it would appear that the parental magma for the Gamoep pipes was itself relatively evolved, since olivine phenocrysts in the Gamoep rocks are always more Fe-rich than would be expected in an unmodified mantle-derived liquid. A consideration of the compositional data suggests that an average Gamoep type magma could be derived from a "primary" magma very similar to an average South African kimberlite by crystal fractionation of the kimberlite megacryst assemblage comprising olivine, ortnopyroxene, clinopyroxene, garnet and ilmenite. Sr isotope evidence is also supportive of a genetic relationship between South African kimberlites and the olivine melilites of Namaqualand-Busnmanland since both have clearly been derived from isotopically "depleted" mantle source areas.

Alkaline volcanic pipes of post-Gondwanaland age show a systematic variation in composition with their geographic position on the southern African subcontinent. Diamondiferous kimberlites, which appear to be the least evolved chemically, are confined to the central, ancient, cratonic areas. More evolved alkaline rocks (olivine melilitites and olivine nephelinites) are concentrated closer to the continental margin in the east and west of South Africa. While the most evolved alkaline rocks (the trachybasalts of the Alphard Banks) occur on the southern continental shelf. It is postulated that this chemical zonation may be related to a steepening of the geotherm from the centre of the subcontinent towards its edges.

C19

THE GEOCHEMISTRY OF SOME KIMBERLITES FROM THE TYPE AREA IN KIMBERLEY SOUTH AFRICA, IN RELATION TO MODELS OF KIMBERLITE PETROGENESIS

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When compared to the available information about more widespread and thoroughly studied rocks such as basalts, considerable uncertainty remains about the chemical composition of kimberlite magmas. This is because the frequently violent emplacement of kimberlite leads to contamination during emplacement, and further renders kimberlite susceptible to post-emplacement alteration by groundwater which can percolate through the relativity permeable tuffs and brecciated kimberlite, for which many analyses appear in the literature. Quietly intruded magmatic kimberlites which are free of crustal inclusions and impermeable groundwater after emplacement are rare. However, some such specimens are included together with altered rocks in a collection of seventy kimberlites for which full major and some trace element analyses are presented in the present work. (See Berg and Allsopp, 1972 and Barret and Berg, 1975 for brief descriptions and isotope data for some of these rocks).

Systematic appraisal of the geochemical data was combined with the petrographic assessment of freshness as described in Barret and Berg (1975). This approach was designed to characterise the geochemistry of kimberlite magma as closely as possible and to identify rocks in which the original kimberlite chemistry has been altered to such an extent that their analyses no longer represent the original kimberlite magma's composition sufficiently closely to be satisfactory for testing models for kimberlite formation. Alteration and contamination lead to increases, for example, in the concentrations of Na_2O and Al_2O_3. There are no significant differences in the concentrations of some elements like MgO between fresh magmatic and altered kimberlites, but many altered kimberlites have significantly higher concentrations of SiO_2 than fresh kimberlites. Those altered kimberlites which do have similar concentrations of SiO_2 to fresh kimberlites, nevertheless have relatively high SiO_2/MgO ratios, as have the altered kimberlites which contain higher concentrations of SiO_2. Care must be taken to distinguish between increases in the concentration of Al_2O_3 and SiO_2/MgO ratios which are due to an increase in the amounts of primary phlogopite in a sample rather than to contamination and alteration reactions.

It was found that composition such as the averages for Lesotho kimberlites given by Dawson (1962) and Gurney and Ebrahim (1973), which have been used by other investigators to represent the chemistry of kimberlite magmas, fall in the range of the altered kimberlites sutied here. An outcome of the alteration of kimberlite is to increase the amount of orthopyroxene in the norm of average compositions, which may lead to incorrect differentiation models and influence the results of high pressure phase equilibrium studies based on the chemistry of average kimberlite. Consequently it is suggested that some current models for the formation of kimberlite and related rocks may require considerable refinement.

Some implications are considered, such as the indicated partition coefficients for Cr and Ni, when the assumption is made that kimberlite is a partial melt of low degree in the mantle, and that the fresh kimberlites here described adequately represent the composition of such kimberlite magma at its source.

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     Lesotho Natl. Dev. Co., Maseru 280-284.

C20

PREDICTION OF THE CHEMICAL EVOLUTION OF MANTLE MAGMAS AT HIGH PRESSURES

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The experimentally determined compositions of solidus liquids along the basaltic (lherzolitic) solidus to 20 kbar in $CaO-MgO-Al_2O_3-SiO_2$ (CMAS) presented by Presnall et al. (1978, Con. Min. Pet. 66, 203), may be used to constrain the buffered values of aAl_2O_3 and $aSiO_2$ in these melts using the approach of Nicholls and Carmichael (1972, Am. Min. 57, 941). The results obtained for plagioclase- and spinel-lherzolite solidus may be extrapolated to pressures relevant ($\sim$ 40 kbar) to solidus melting of garnet-lherzolite in CMAS. Attempts have been made to use the Flory-Huggins formalism for silicate liquids (Bottinga and Richet, 1978, E.P. S.L. 40, 382) to incorporate Na_2O, FeO, Cr_2O_3, H_2O, CO_2, and K_2O into the appropriate mineral phases and the solidus liquids. The predicted melt evolution may be checked against carefully selected melting experiments at high P relevant to mafic, ultramafic, ultrapotassic or kimberlite magma generation. Furthermore, these results may be used to constrain some of the physical properties relevant to magma segregation, accumulation, and ascent.

C21

LAYERED MANTLE GENERATED THROUGH CONVECTIVE PROCESSES. A MODEL WHICH CAN EXPLAIN THE MANTLE HETEROGENEITIES.

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The models which attempt to explain the upper mantle nature and evolution are constrained
1) by the high homogeneity of the common CaO-rich lherzolites derived from the mantle
2) by the noticable heterogeneities which must exist as indicated by the OIB characteristics and the nodule diversity.

The orogenic lherzolite-type bodies (upper mantle samples) display a pyroxenite layering, the composition of which indicates that it should result from a rather complex history of the upper mantle with successive partial melting events and crystallization of the melts produced (1).

An evolution model for the upper mantle has been developped explaining the generation of such a layering through the effect of convection processes (generation of melts, crystallization etc.)

It is emphasized that the mantle heterogeneities inferred from the OIB can be explained by the existence of such a layering. In this model, the OIB would result from partial melting of these pyroxenite layers. Geochemical data for MORB and OIB as well as the nodule characteristics tend to support such a model. The kimberlite genesis is discussed, on the basis of this model.

(1) LOUBET M. and ALLEGRE C.J. (1982) submitted to Nature.

C22

KIMBERLITE-CARBONATITE: EVOLUTIONARY LINKS?

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The meteoritic impact hypothesis, recently revived to explain the demise of the dinosaurs et al., has received considerable attention and publicity. In this, extra-terrestrial intervention culminates in a global climatic warming causing extinction. To many this explanation is unsatisfactory, not least because of the conspicuous lack of preservation of an appropriate crater. Nonetheless the iridium anomaly at the Cretaceous-Tertiary boundary appears well-documented and seems to require explanation by any alternative hypothesis.

Radiometric dating of rocks of the carbonatite-kimberlite clan has indicated that certain times were particularly favourable for their emplacement. A coincidence between these and several Phanerozoic period boundaries is also evident. It therefore seems plausible that an enhanced input of CO_2 to the atmosphere at these times caused global warming and resulted in extinctions. Perhaps these intrusions have, in addition, exhumed from depth and superficially dispersed the platinum group metals, thus accounting for the iridium anomaly observed stratigraphically.

The above proposal may readily be tested by additional accurate age determinations on kimberlites and carbonatites to better define their distribution in time and by radiochemical activation analysis for Group VIII metals, if suitable samples are obtainable. The information presently available and pertaining to this intriguing problem will be discussed and assessed.

Tom Jordan and others examining the Wyoming-Colorado Stateline kimberlite during Navajo field trip
Photo C. Frostevaux

D   Xenoliths and geometers

D1

ENSTATITE-DIOPSIDE SOLVUS TO 60 KB

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The width of the pyroxene solvus in the simple system enstatite-diopside as a function of pressure and temperature is an important constraint for the use of the composition of natural pyroxenes from lherzolites as a geothermometer. Experimental data have been obtained so far only up to 40 kb (only at 1200°C at this pressure). Thermodynamic models based on high pressure experiments and calorimetric data should not be extrapolated above 40 kb according to the authors (e.g.Lindsley, 1980). However pressures up to 90 kb have been estimated in some garnet lherzolites so that an extrapolation of the pyroxene solvus above 40 kb is necessary to estimate the temperature of many garnet lherzolites. With a well-calibrated belt-apparatus (against the silver-melting curve and the quartz-coesite transition) I have now embarked to determine the pyroxene solvus up to 60 kb. Pressures are controlled within 300 bars and the temperature to $\pm 1°C$ (estimated accuracy ± 0.5 kb and $\pm 10°C$). Starting materials are mixtures of synthetic enstatite and diopside and for reversals glass of the same bulk composition. So far experiments have been carried out at 40 kb at 1100°C, 1300°C and 1500°C and at 1300°C at 50 kb and 60 kb. The compositional brackets from the experiments for the solvus at 1300°C are given in Table 1. The data are consistent with experimental data given in the literature. They indicate that, at 1300°C, the influence of pressure on

	En $x_{CaMgSi_2O_6}$	Di $x_{CaMgSi_2O_6}$
40 kb	0.052	0.78-0.8
50 kb	0.045-0.048	0.785-0.815
60 kb	0.036-0.038	0.79-0.83

the position of the solvus becomes less with increasing pressure. An extrapolation of the currently available models on the P, T-dependance of the pyroxene solvus shows that temperature estimates can be too high by up too 250°C at 60 kb.

Lindsley, D.H., Min.Soc.Rev.Min.7 (1980) 289

D2

GEOTHERMOMETERS AND GEOBAROMETERS FOR SPINEL-BEARING ULTRAMAFIC ROCKS

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A series of two pyroxene, spinel-bearing assemblages have been synthesized over the temperature and pressure range from 900°C to 1300°C and 10Kb to 15Kb, respectively. Systematic compositional variations have been introduced by varying the composition of the reactants in the following synthesizing reaction.

Garnet + Olivine = Al-Pyroxene + Spinel

In this way it has been possible to experimentally examine the competing effects of Cr and Al substitution in coexisting pyroxenes and spinels.

The synthesized products have been analyzed with an electron microprobe and used to empirically define expressions that describe exchange reactions between coexisting phases. The results yield a series of geothermometers for Al/Cr exchange between coexisting pyroxenes and spinels, Fe/Mg exchange between coexisting silicates and silicates and spinels. For the compositions with observed pressure dependence of the orthopyroxene-clinopyroxene solvus yields a useful geobarometer for these phase assemblages

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D3

THE OLIVINE-CLINOPYROXENE GEOBAROMETER: IMPLICATION FOR THE THERMAL STRUCTURE OF THE UPPER MANTLE NEAR THE RIO GRANDE RIFT

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Ca-Mg exchange between olivine and clinopyroxene has been studied in the system MgO-CaO-SiO$_2$ in the temperature range 1100-1500°C and pressure range 9-41 kb. Ca in olivine decreases with increasing pressure as a result of Ca going into the higher coordination M2 site of clinopyroxene. For the Ca-Mg exchange reaction between olivine and clinopyroxene, $\Delta V^0 = 0.249$ j/bar/mole, sufficient for pressure estimates precise to ± 3 kb if temperatures of equilibration are independently known.

The olivine-clinopyroxene geobarometer can be used as an independent check on results from pyroxene barometry applied to garnet lherzolites. Also, it does not encounter the problems inherent in pyroxene barometry of spinel lherzolites. The olivine-clinopyroxene barometer has been applied to

xenoliths from several localities to determine local geotherms, after making assumptions about the activities of various components in the natural solid solutions. Results on southern African peridotites compare favorably with pressure estimates made by independent geobarometers and with calculated continental conduction geotherms. Results from southwestern United States, however, indicate that the geotherm is elevated, though not to the extent of mid-ocean ridge convection geotherms. This may be due to an intermediate thermal state, involving both convection and conduction, resulting from the slow rate of spreading occurring along the Rio Grande Rift.

D4

GARNET LHERZOLITES FROM THE HANAUS-I AND LOUWRENSIA KIMBERLITES, NAMIBIA

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The Gibeon cluster of Namibian kimberlites is emplaced into the Orange River Belt which has accreted to the Transvaal craton. These "off-craton" kimberlites are non-diamoniferous and are younger than the diamond bearing "on-craton" kimberlites. The Hanaus-I and Louwrensia kimberlites each contain a bimodal suite of upper mantle-derived garnet lherzolite xenoliths characterized by a coarse granular or a porphyroclastic-mosaic texture. The Louwrensia pipe in addition contains garnet harzburgites in which the orthopyroxenes have exsolved lamellar clinopyroxenes. Deformed lherzolites are not iron-enriched relative to the deformation-free types. Temperatures and pressures of equilibration calculated by the Wells-Wood method are from 915-1050°C at 27-36 kb and 915-1010°C at 29-41 kb for coarse lherzolites from Hanaus and Louwrensia respectively, and from 1000-1225°C at 26-39 kb and 1010-1125°C at 33-34 kb for porphyroclastic-mosaic types from Hanaus and Louwrensia respectively. The coarse types from both localities have similar equilibration P and T's to coarse lherzolites from on-craton kimberlites and plot on the lower non-inflected limb of the South African continental shield "paleogeotherm" defined by such lherzolites. The deformed lherzolites plot randomly above this geotherm and do not define an inflected limb. These higher equilibration temperatures are considered to be due to heating, shearing and recrystallization of mantle during kimberlite formation. The lherzolite mineral compositions and equilibration conditions indicate that the Namibian kimberlites have been derived from similar depths to on-craton kimberlites and have incorporated similar mantle material. The lack of diamonds is not a consequence of derivation from atypical mantle or from regions with an unusual geothermal gradient.

D5

GARNET PERIDOTITES FROM WILLIAMS KIMBERLITES, NORTH-CENTRAL MONTANA, USA

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Two Williams kimberlites, 250x350m and 37x390m, in the eastern part of a swarm of 30 middle Eo-cene alnoitic diatremes, contain xenoliths of garnet-bearing lherzolites, harzburgites and dunites. Temperatures were calculated by the Lindsley-Dixon 20 kb method for lherzolites and and by the O'Neill-Wood method for harzburgites and dunites and pressures were calculated by the MacGregor method, or were assumed to be 50 kb for dunites. Most peridotites equilibrated at 1220-1350°C and 50-60 kb, well above a 44 mW/m² shield geotherm and on or at higher P than the graphite-diamond boundary. Three lherzolites show low T-P (830-940°C, 23-42 kb) and are close to the shield geotherm. All three low T-P lherzolites have coarse texture whereas the high T-P cluster has both coarse and porphyroclastic textures, indicating a range of conditions of deformation and recrystallization in a restricted high T-P range. Maximum size of large strained olivines is as much as 2 cm. The tiny size (0.1-0.2 mm) of granulated and euhedral olivines in several xenoliths shows that deformation was occurring just prior to incorporation in kimberlite and that ascent was rapid enough to retard further coarsening of fine-grained olivine. For other high T-P peridotites, cessation of deformation before inclusion in kimberlite is suggested by larger (2mm) euhedral olivines in a matrix of fine granulated olivine or by optical continuity of large and nearby small olivines. Two low T-P lherzolites contain 5-8mm clots of moderate-Cr garnet + Cr-spinel + Cr-diopside inferred to form by reaction of an initial high-Cr garnet brought into the garnet+spinel stability field. This suggests a slower ascent or pause in ascent, compared with other peridotites containing inclusion-free, high-Cr garnets. Textural and compositional variations of peridotites are compatible with kimberlite generation and ascent during dynamic diapiric perturbation of the upper mantle.

D6

MANTLE GARNET-SPINEL TRANSITION ZONE DEMONSTRATED BY XENOLITHS FROM COLORADO-WYOMING KIMBERLITES

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Two groups of xenoliths containing coexisting garnet and spinel have been recovered from Colorado-Wyoming kimberlites. The first group consists of pyroxenites with coarse-grained, pale green, aluminous spinel that is relatively Mg-rich and Cr-poor. Garnet in these xenoliths appears to be exsolved from aluminous pyroxene, and occurs as lamellae and as grain boundary rims surrounding pyroxenes and spinels. Xenoliths of the second group are peridotites containing fine-grained vermicular, reddish-brown spinel that is more enriched in Fe and Cr relative to Al. Some garnet in these nodules also occurs as exsolution lamellae in pyroxene, but most engulfs spinel and probably formed by the reaction *orthopyroxene + clinopyroxene + spinel = olivine + garnet* as suggested by MacGregor (1970). Utilizing MacGregor's (1974) orthopyroxene geobarometer, mineral equilibration depths of 50-100 km and 25-60 km have been calculated for the peridotite and pyroxenite xenoliths, respectively. Temperature estimates range between 590-800°C. Garnet in both xenolith groups apparently formed during or immediately prior to kimberlite emplacement and the

resulting metastable textures probably owe their preservation to the relatively rapid transport of nodules to the surface in kimberlite magma. Garnet exsolution from pyroxene could have been facilitated by decreased temperatures accompanying kimberlite cooling. Formation of peridotite suite garnet by the above pyroxene-spinel reaction also may have been induced by decreasing temperatures; however, locally higher pressures possibly associated with tectonic adjustments related to intrusion of kimberlite may have perturbed the garnet-spinel phase boundary triggering crystallization of garnet at shallower mantle depths. (Study supported by Earth Sciences Section of NSF, Contract EAR-7810775)

D7

GARNET-PYROXENITES ASSOCIATED WITH THE ULTRAMAFIC ROCKS: ECLOGITES, ARIEGITES, GRIQUAITES OR GROSPYDITES ?

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Garnet(py-al) + clinopyroxene associations related to metamorphic rocks were termed "eclogites" by Hauy (1822). this appellation designs also various gt-cpx assemblages related to ultramafic bodies or xenoliths. So the same appellation classify different types of gt-cpx bearing rocks whereas different names are still used to qualify the same class of rocks. It is suggested :
1- To keep "eclogite" for rocks associated with high-pressure/low-temperature metamorphic units. Most of them are saturated in silica and the clinopyroxene is Jd.rich and Ca.Ts-poor. Silica undersaturated compositions may involve corundum in their parageneses.
2- To consider the high pressure/ high temperature gt-cpx rocks :
   a) As "ariegites" when orthopyroxene and spinel are also abundant phases. The ariegites, characterizing the high pressure subfacies of spinel-lherzolite facies (O'Hara, 1967), would breakdown at higher pressure to give gt-harzburgites or -wehrlites.
   b) As "griquaites" when clinopyroxene and garnet are the main phases (plus or minus spinel). The griquaites equilibrated in the ariegite subfacies as well as in the garnet-lherzolite facies.
   c) As "grospydites" when garnet and clinopyroxene are associated with kyanite and/or corundum. Such rocks are characterized by Ca-rich garnet with Ca.Ts and Jd.rich clinopyroxene ; giving a larger acceptation to this word than previously defined by Bobriyevich et al. (1960), the grospydites would involve most of corundum and kyanite associated with kimberlites. They cristallized at very high pressure in the ariegite subfacies or in the garnet-lherzolite facies.

D8

PETROLOGY OF A SUITE OF ECLOGITE INCLUSIONS FROM THE BOBBEJAAN MINE, SOUTH AFRICA:
I. MAJOR PHASE CHEMISTRY

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A suite of more than forty eclogite samples from the Bobbejaan kimberlite, near Bellsbank, South Africa, has been examined in thin section and major phases have been analysed by electron microprobe. Most samples are biminerallic eclogites, although a few contain up to 20% apparently primary phlogopite. Primary accessory phases include sulfides (pyrrhotite, pentlandite, chalcopyrite), kyanite, rutile, and graphite. Also, two corundum grospydites are described in a companion paper.

Some systematic trends are observed in the major-element chemistry of the principal phases.
1) The more calcic garnets occur with the more aluminous clinopyroxenes, and conversely, the more Fe- and Mg-rich garnets occur with the more aluminum-poor clinopyroxenes.
2) When temperatures are estimated from the Fe-Mg distribution between garnet and clinopyroxene, the highest apparent temperatures correlate with the highest Fe contents of both clinopyroxene and garnet, and the lowest temperatures correlate with the most calcic garnets and aluminous clinopyroxenes.

It is postulated that these inclusions are a suite (or suites) of igneous eclogites derived by magmatic differentiation at pressures between 25 and 40 Kbar. If this is true, the generalized chemical trends observed may be representative of high pressure differentiation within the alkali basalt system.

D9

PETROLOGY OF A SUITE OF ECLOGITE INCLUSIONS FROM THE BOBBEJAAN MINE, SOUTH AFRICA:
II. TWO UNIQUE CORUNDUM GROSPYDITES

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Two small corundum grospydite inclusions from the Bobbejaan kimberlite, near Bellsbank South Africa, have been observed in thin section and analyzed by electron microprobe. One sample (SBB-2H) contains approximately 60% garnet ($Gr_{48}Py_{37}Alm_{15}$), 35% clinopyroxene ($Jd_{52}Di_{38}CaTs_7$), 5% kyanite, and less than one percent corundum. The second (SBB-3P) contains 58% garnet ($Gr_{48}Py_{37}Alm_{16}$), 25% clinopyroxene ($Jd_{55}Di_{36}CaTs_9$), 14% kyanite, and 3% corundum. In both samples most corundum is observed as inclusions in kyanite, but in the second sample it is also observed as inclusions in garnet. In neither sample is corundum observed in contact with pyroxene.

In this second sample clinopyroxenes are observed to include lamellae of both kyanite and garnet in an apparent exsolution texture. If the kyanite and garnet lamellae in this clinopyroxene were once a single pyroxene, it would have a composition of approximately 30% $CaAl_2Si_4O_{12}$, 40% jadeite, and 20% diopside. Such pyroxene compositions have not been reported in kimberlite eclogites but may be stable at pressures in excess of 40 Kbar.

It is postulated that these two grospydites formed by magmatic differentiation within the eclogite system at pressures between 40 and 60 Kbar and subsequently re-equilibrated at pressures between 25 and 35 Kbar. The initial phases were garnet, clinopyroxene, and corundum, plus possible kyanite. Breakdown of the $CaAl_2Si_4O_{12}$-rich pyroxene to form clino-

pyroxene, garnet, kyanite, and silica gave rise to the garnet and kyanite lamellae in the clinopyroxene. The excess silica from the reaction would have reacted with corundum to form kyanite in the observed texture.
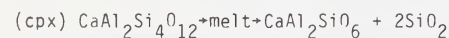
D10

PETROLOGY OF A SUITE OF ECLOGITE INCLUSIONS FROM THE BOBBEJAAN MINE, SOUTH AFRICA. III. PARTIAL MELTING, RECRYSTALLIZATION AND P-T TRAJECTORIES

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A suite of eclogite nodules from the Bobbejaan Mine near Bellsbank, South Africa, all show partial melt textures and evidence of recrystallization at intermediate pressures. Most of the nodules are typical bimineralic eclogites that are associated with kimberlites, however some may contain primary phlogopite. Accessory phases are rutile, pyrrhotite and pentlandite. Jadeite components in unaltered clinopyroxene cores range from 15% to 40% by weight and may contain appreciable $Ca_{0.5} Al Si_2O_6$ (to 10 wt%). Garnet cores can contain up to 75 mol% pyrope but commonly have subequal pyrope and almandine components with up to 40% grossularite.

The epitaxial recrystallization rims of the phases show very different compositions from the cores. Clinopyroxene rims show low jadeite (to 5 wt%) and higher Ca-Tschermaks components; stoichiometry calculations indicate up to 12 wt% acmite and the absence of $Ca_{0.5} AlSi_2O_6$. Recrystallization phases around garnet rims are primarily orthopyroxene and spinel. The following recrystallization reactions are typical for these clinopyroxene and garnets:

$$(cpx) \quad CaAl_2Si_4O_{12} + melt \rightarrow CaAl_2SiO_6 + 2SiO_2$$

$$(gt) \quad Mg_3Al_2Si_3O_{12} + melt \rightarrow MgAl_2O_4 + 2MgSiO_3 + SiO_2$$

Pressure and temperature estimates of the crystal cores indicate that the diamondiferous eclogites equilibrate at 950° - 1100°C and 35-45 Kb. These eclogites have partially melted and recrystallized near the spinel-garnet lherzolite boundary. Aluminum content in orthopyroxene yields temperature estimates of 1250° to 1300°C while spinel chemistry (high Al/Cr) and the absence of garnet indicate pressures of 20-22 Kb during the partial melt and recrystallization episode.

D11

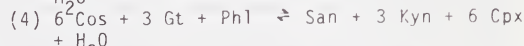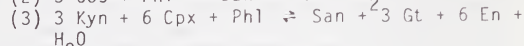### ORIGIN OF A SANIDINE-COESITE GROSPYDITE

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A grospydite xenolith from the Roberts Victor kimberlite pipe in South Africa presents an unusual phase assemblage of clinopyroxene, garnet, kyanite, coesite, and sanidine. The rock as previously described consists of 50% omphacitic clinopyroxene, 28% garnet ($Gr_{50} Py_{28} Alm_{22}$), 9% kyanite, 6% coesite, and one percent sanidine (Or_{99}). Assuming the addition of three additional compatible phases (phlogopite, enstatite, and H_2O vapor) and a simplified chemistry of the phases present a Schreinemakers thermodynamic analysis was attempted in order to

estimate the pressure and temperature of equilibrium of the rock.

Four reactions involving six components are likely to have determined an invariant point for the assemblage.

(1) Kyn + 2Cpx $\rightleftharpoons$ Cos + Gt + En
(2) 3 Cos + Phl $\rightleftharpoons$ San + 3En + H_2O
(3) 3 Kyn + 6 Cpx + Phl $\rightleftharpoons$ San + 3 Gt + 6 En + H_2O
(4) 6 Cos + 3 Gt + Phl $\rightleftharpoons$ San + 3 Kyn + 6 Cpx + H_2O

Using tabulated as well as estimated thermodynamic data for the phases, the calculated values for equilibrium temperatures and pressures for the reactions yield an invariant point for the assemblage at a depth of about 104 km (32 kbars) and a temperature near 1180 K.

D12

INCLUSIONS IN THE LAKE ELLEN KIMBERLITE, NORTHERN MICHIGAN, USA

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The recently discovered Lake Ellen kimberlite indicates that bedrock sources of diamonds in glacial deposits in the Great Lakes area could lie within the northern U.S. Magnetic surveys show that the poorly exposed kimberlite is 200m in diameter and has a body 25x90m(?) adjacent to it. The kimberlite cuts Proterozoic volcanic rocks that overlie Archean basement, but is post-Ordovician on the basis of abundant Ordovician(?) dolomite inclusions. Xenocrysts and megacrysts are ilmenite (abundant, 13-15% MgO), pyrope-almandine and Cr-pyrope (up to 9.3% Cr_2O_3), Cr-diopside (up to 4.5% Cr_2O_3) olivine (Fo 91), enstatite and phlogopite. The kimberlite sampled crustal schist and granulite, during emplacement, as well as a heterogeneous upper mantle represented by disaggregated crystals or rare xenoliths of eclogites, garnet pyroxenites and garnet peridotites. Eclogites, up to 3 cm size, show granoblastic equant or tabular textures and consist of jadeitic cpx (up to 8.4% Na_2O, 15.3% Al_2O_3), pyrope-alamandine, $\pm$ rutile+kyanite+sulfide. Garnet pyroxenite contains pyrope (0.44% Cr_2O_3) + cpx (0.85% Na_2O, 0.63% Cr_2O_3) + Mg-Al spinel. Mineral compositions of rare composite xenocrysts of garnet + cpx are distinctively peridotitic, pyroxenitic or eclogitic. Temperatures (T) of equilibration are 900-1020°C for the eclogites and 785-845°C for the garnet pyroxenite using the Ellis-Green method. Kyanite-bearing eclogites must have formed at pressures greater than 18-20 kb. Using the present heat flow value of 44mW/m² (shield geotherm) for the time of kimberlite emplacement, the eclogite T's imply pressures of 33-44 kb (105-140km) and the garnet pyroxenite T's indicate pressures of 24-29 kb (75-90 km). Five peridotitic garnet-cpx composite xenocrysts have T's of 880-1125°C (Lindsley-Dixon, 20 kb solvus); T's of three, if on a shield geotherm, imply pressures within the diamond stability field.

D13

PETROLOGY OF THE EGLAZINES KIMBERLITE-LIKE INTRUSION

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The Eglazines pipe belongs to the Causses

volcanic province where only alkali basalts occur, usually bearing high-pressure phases (megacrysts, spinel-garnet pyroxenites of the Al-Ti-augite group, spinel-peridotites and at Eglazines also spinel-garnet pyroxenites and spinel-garnet peridotites).

Two new geothermometers, one new geobarometer and one new "oxygen fugacitimeter" are used in this study.

The pyroxenites include spinel-free pyroxenites equilibrated from 1160 to 1220 C°, spinel websterites (1000 → 1050 C°) and spinel-garnet pyroxenites. Spinel peridotites are composed of two groups. The former consists of coarse-grained peridotites equilibrated near 1000 C° (f $O_2 \approx 10^{-10}$ atm.) the latter group is composed of peridotites (1200 → 1250 C°) reminding of some porphyroclastic peridotites from kimberlite xenoliths of South Africa.

The spinel-garnet peridotites plot into the lherzolite field. Thin section observations suggest that spinel is not the result of resorption (by lowering of pressure) of an earlier garnet-bearing rock. Therefore these xenoliths may be assigned to the spinel-garnet boundary. It would have equilibrated near 25 kb at a temperature of some 1230 C° (f $O_2 \approx 10^{-95}$ atm.).

D14

PERIDOTITES FROM THE OLMANI SCORIA CONE, N. TANZANIA

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Basaltic scoria of the Olmani volcano, 10km SE of Arusha, N. Tanzania, contains blocks of dunite, harzburgite, lherzolite and diopside-rich wehrlite. The texture of most is porphyroclastic; large (>1cm) deformed olivine grains exhibit multiple planar extinction discontinuities, and there is abundant evidence for grain-boundary migration between adjacent deformed grains; subgrains are also developed. In orthopyroxenes, exsolution of opaque platelets takes place at extinction discontinuities. Large olivines are forsterite (Fo$_{92-93}$), but smaller re-crystallized, strain-free grains are more Fe-rich (Fo$_{88}$). Enstatite (En$_{90-92}$) is low in Al$_2$O$_3$ (1-2wt %) and Ca (0-0.4), Both enstatite and Cr-diopside (mg 0.93, up to 2.2% Na$_2$O, up to 3.2% Cr$_2$O$_3$) may occur in "fingerprint" intergrowths with Mg-chrome spinel (MgO 12-15%, Cr$_2$O$_3$ 52-66%). Fine-grained material (?devitrified glass) associated with some cpx-chromite intergrowths is K-rich (4.7-5.7%) and very variable in composition (e.g. SiO$_2$ 46-54%, MgO 4-19%, CaO 1-3%) and with low totals (?hydrous). In one specimen high-Na glass of variable composition (e.g.Na$_2$O 6.2-8.2%, K$_2$O 2.7-4.0, SiO$_2$ 44.2-49.9) but apparently anhydrous (totals 98.4-101.3), has developed adjacent to cpx grains. The development of these alkali-rich basic melts from upper mantle material may be significant in models for the alkali-basalt province of N. Tanzania

D15

GARNET LHERZOLITE AND OTHER INCLUSIONS FROM A BASALT FLOW, BOW HILL, TASMANIA

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Garnet lherzolite xenoliths at Bow Hill, Tasmania are a rare occurrence from a basalt flow. Such xenoliths are known from alkali basalt (mainly breccias) in France, U.R.S.S., Mongolia, Patagonia, Japan, Hawaiian Islands and E. Australia. The Tasmanian examples occur with garnet websterite, spinel lherzolite, spinel websterite, spinel wehrlite and crustal inclusions. Statistical counts give a ratio of garnet lherzolite to spinel lherzolite of about 1 to 500 and between 60-75 % peridotites, 5-10 % pyroxenites and 20-30 % crustal rocks for the suite. Apart from cumulate spinel wehrlite, the ultramafic inclusions represent accidentally derived mantle material.

The garnet compositions (Mg$_{70-78}$Fe$_{13-18}$Ca$_{8-13}$) lie at the magnesian extreme for E. Australian basaltic and kimberlitic inclusions. They occur with Al orthopyroxene (Mg$_{83-89}$Fe$_{9-14}$Ca$_2$), Al clinopyroxene (Mg$_{52-54}$Ca$_{38-41}$Fe$_{4-9}$) ± olivine (Mg$_{90-93}$). Compositions are based on micro-probe analyses with total Fe as Fe O.

The host nepheline hawaiite belongs to a Tertiary, mafic K-rich alkaline lineage in Tasmania. The megacryst and cumulate minerals include olivine (Mg$_{82}$), Al clinopyroxene (Mg$_{42-46}$Ca$_{44-49}$Fe$_{9-11}$) and spinel (Mg$_{85}$Fe$_{35}$). Chemical mixing by addition of observed proportions of these compositions suggest that the host evolved by 20 % crystallisation of wehrlite from a primary parental basanite. Similar basanites are found in the area.

P-T estimates for the garnet lherzolite and garnet websterite from a variety of geobarometers and geothermometers range between 17-31 kb and 1130-1320°C. (Carswell and Gibbs, 1980, Nodmins programme ; Herzberg, 1978). This data indicates an origin in the mantle lying without the diamond stability zone. The lower P-T values may be the more realistic as they match experimental sub-liquidus crystallisation of wehrlite minerals from compositions related to the parental basanite (< 26 kb, 1300°C ; Arculus, 1975).

The xenolith assemblages allow a composite reconstruction of the lower crust and upper mantle under central Tasmania. The mineral compositions demonstrate the care needed to distinguish true kimberlites from basaltic occurrence, using similar indicator minerals.

Arculus R.J., 1975 Carnegie Inst. Washington Yearb,74,512-515
Carswell D.A., Gibbs G.F.G., 1980 Contrib. Mineral Petrol, 74 403-416
Herzberg C.T., 1978 Geochim.Cosmochim.Acta., 42, 945-957

D16

PETROLOGY AND GEOCHEMISTRY OF MANTLE ECLOGITE XENOLITHS FROM COLORADO-WYOMING KIMBERLITES

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Eclogite xenoliths from Colorado-Wyoming kimberlites can be divided into two groups based essentially on absence or presence of kyanite and(or) corundum, and corresponding metaluminous or peraluminous character. Metaluminous eclogites generally are granoblastic and contain one or more of the accessory phases rutile, sanidine, graphite, quartz and sphene. Peraluminous eclogites commonly are foliated or layered and may contain accessory rutile and sanidine. Compositions of clinopyroxene and garnet overlap between the two groups; however, clinopyroxenes in peraluminous xenoliths generally are higher in jadeite and Ca-Al components, whereas garnets are higher in grossular component and lower in almandine. Equilibration temperatures, calculated from Fe-Mg partitioning between clinopyroxene and garnet, range from 794ºC to 1163ºC for an assumed pressure of

30 kilobars. Normative bulk compositions of the eclogites are equivalent to picrite, olivine tholeiite, alkali olivine basalt, basanite and basaltic anorthosite. Compared to equivalent phases precipitated from laboratory melts, eclogite clinopyroxenes contain higher jadeite and SiO_2 and lower Ca-Tschermak molecule, whereas garnets contain higher grossular. Eclogite bulk compositions are dissimilar to those of mafic liquids derived by partial melting of mantle peridotites. Eclogites contain higher Al_2O_3, Na_2O and locally K_2O, and lower MgO and Cr_2O_3. Such compositions are similar to those of clinopyroxene + garnet ± kyanite ± feldspar cumulates precipitated from tholeiitic and calc-alkaline laboratory melts. Chemical compositions support the hypothesis of Green and Ringwood (1967) that the eclogites may be metamorphosed residua and cumulates from partially melted subducted oceanic crust. (Study supported by Earth Sciences Section of NSF, Contract EAR-7810775)

D17

ILMENITE IN UPPER MANTLE POLYMICT XENO-LITHS FROM BULTFONTEIN

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Four polymict deformed xenoliths from Bultfontein, each of which have a strong disequilibrium garnet lherzolitic mineralogy, also contain abundant ilmenite. The ilmenite occurs either as transgressive veins or as isolated patches and 'blebs' and is closely associated with phlogopite and often rutile as well as occasional sulphides. The ilmenite in the various xenoliths broadly have similar compositions being characterised by high but variable Cr_2O_3 (1-5 wt.%) contents and relatively constant and high MgO (14-15 wt.%) contents, while the rutile is also often enriched in Cr_2O_3 (3-4 wt.%). Where the ilmenite occurs as veins, which are clearly intrusive into the xenoliths, the smaller veins and the edges of the larger veins invariably have the higher Cr_2O_3 contents, perhaps in response to temperature variation during crystallisation. No armalcolite has been found which is suggestive of a high pressure (more than 20 kb) paragenesis for the ilmenite. The mineral chemistry of the ilmenite and rutile is described in detail and is also compared to xenocrystal material and available experimental data. This information is used to develop a possible phenocrystal model of formation for the majority of the ilmenite which occurs in kimberlite.

D18

PETROLOGY AND GEOCHEMISTRY OF ULTRA-MAFIC XENOLITHS FROM THE GERONIMO VOL-CANIC FIELD

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Ultramafic xenoliths included in Plio/Pleisto-cene alkali basalts from the Geronimo Volcanic Field (GVF) record a multistage evolution for the mantle beneath SE Arizona. The dominance of un-foliated, granuloblastic, Type I harzburgites and clinopyroxene-depleted spinel lherzolites at GVF supports the occurrence of a major depletion event in the mantle followed by a period of re-equilibration. The coherence of major element mineral chemistry data indicates that variation in bulk rock major element chemistry among the xenoliths is a function of modal mineral abundances and that equilibration conditions were relatively uniform. Variation in Fe/Mg and REE abundances indicates different degrees of deple-tion among the xenoliths. INAA analyses of REE in cpx from cpx-rich spinel lherzolites have high, LREE-enriched patterns while cpx from de-pleted (cpx-poor) spinel lherzolites and harz-burgites may be as much as an order of magnitude lower in REE.

Composite xenoliths are abundant and of two types: 1) websterite or diopside veins in spinel lherzolite, and 2) Type II clinopyroxenite cross-cutting wehrlite or spinel lherzolite. Chem-ically, the Type II clinopyroxenites are distin-guished from the Type I xenoliths by higher Al, Ti, Ca and Na, but lower Mg. They typically possess igneous textures in which cpx subpoiki-litically to poikilitically encloses olivines and probably formed as the crystallization of magma in dikes or conduits under mantle conditions.

Kaersutite peridotites, similar to the Type II spinel-bearing clinopyroxenites, are locally abundant. The kaersutite commonly forms large, cm-sized, optically continuous crystals which partially replace clinopyroxenes of varying crystallographic orientations. The origin of the amphibole is enigmatic, but may represent the final, fluid-rich stage of crystallization of magma trapped at depth.

D19

TWO-PYROXENE INTERGROWTHS FROM SOUTH AFRICA

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Megacrysts consisting of two-pyroxene inter-growths in which one of the phases has obviously exsolved from the other have been investigated. These megacrysts were obtained from Koffiefon-tein, and the Bellsbank area kimberlites. All previous studies of megacrysts to date have been for the most part on discrete mineral grains. Conclusions made from such studies are based on the assumption that the discrete megacrysts may have formed in equilibrium. In the case of the 2-pyroxene intergrowths no assumption is necessary as it is a fact that the two phases have equilibrated together.

The pyroxenes forming the intergrowths are typically diopside-enstatite. In some instances minor garnet either as lamella or rounded blebs is present. Either enstatite or diopside may be the host with the other mineral occurring as the exsolved phase. All analyses of the clinopyroxenes and orthopyroxene pairs were used in determining pressures and temp-eratures of equilibration via the computer program TEMPEST. Temperature (Lindsley and Dixon, 1976) versus pressure (Wells, 1977) plot for the Bellsbank intergrowths define a geotherm generally similar to ones suggested for other kimberlites in the region. It appears that most of the intergrowths have cooled to the geotherm and there is little evidence for abnormal temperature environ-

ments. Samples at the extreme ends of the geotherm differ by 220°C and reflect depth differences of the order of 60km. These results together with those of Koffiefontein and Frank Smith suggest that many megacrysts may have come from widely differing depths and environments in the mantle.

D20

SINGLE-CRYSTAL STRUCTURE REFINEMENTS OF SUPER-SILICIC CLINOPYROXENES FROM THE ZAGADOCHNAYA KIMBERLITE PIPE, YAKUTIA, USSR.

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It has often been suggested that supersilicic (cation-deficient) clinopyroxenes contain vacant sites, probably in the form of solid-solution of the CaEs end-member ($Ca_{0.5}Al_1Si_2O_6$), but full structure refinements by X-ray diffraction have not previously been made. Refinements are now presented for optically-clear supersilicic clinopyroxenes from two grospydite nodules from the Zagadochnaya kimberlite pipe.

In sample Zaga/0, both refinements and electron microprobe analysis indicate intergrain inhomogeneity but intragrain homogeneity. The refinements are compatible with vacancies in M2 and with the microprobe analysis ($Jd_{.45}$ $Di_{.38}CaTs_{.07}CaEs_{.10}$), but they do not prove the existence of vacancies in M2. The space group is C2/c such that this is the only confirmed disordered omphacite with around 50 % Jd. This primary clinopyroxene co-existed with garnet, kyanite and corundum, but has been partially replaced by secondary clinopyroxene ($Jd_{.17}Di_{.66}$ $CaTs_{.17}$), clinoamphibole, plagioclase, quartz and zoisite. This rock thus displays the simultaneous expulsion of excess SiO_2 and breakdown to an amphibolite-facies paragenesis.

Sample Zaga/8 differs in containing secondary clinopyroxene in an exsolution texture. Both samples share some features in common with certain supersilicic clinopyroxenes from the Roberts Victor kimberlite pipe, S. Africa, though direct exsolution of SiO_2 has not been observed in these Zagadochnaya samples.

D21

ON THE CHARACTERISATION AND CREDIBILITY OF SUPERSILICIC, STOICHIOMETRIC, AND SUBSILICIC PYROXENES

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X_{n-s} = 100 $(S-(N+D))/(S+N+D)$% in the natural chemical system SAND (where S = Si + Ti, A = Al + Fe3 + Cr - Na - K, N = 2Na + 2K, and D (divalents) = Ca + Mg + Ni + Fe2 + Mn, all in cation proportions) is proposed as a useful indicator of pyroxene non-stoichiometry. The S : A : (N+D) diagram conveniently demonstrates : 1. supersilicic, stoichiometric, or subsilicic pyroxenes for which X_{n-s} is positive, zero or negative, respectively ; 2. the irrelevance of trivalent cations to pyroxene stoichiometry (since their oxides also have 4 cations (C) per 6 oxygens (0), such that X_{n-s} isopleths radiate from the A apex ; 3. that supersilicic pyroxene is most simply considered as a solid solution of stoichiometric pyroxene with SiO_2 rather than with any A-bearing end-member ; 4. the im-

probable existence of subsilicic pyroxene which requires C>4 per 0=6 ; 5. the "bimineralic eclogite line" between A and $(N+D)_2S_2$ upon which lie all stoichiometric pyroxenes and garnets.

All theoretical supersilicic pyroxene end-members (e.g. $D_{.5}AS_2O_6$, $DA_{.67}S_2O_6$) have no N, since in alkali pyroxene all other cation sites already have the highest-valent cation possible. However, Jd solution aids the stability of M-site vacancies, more so than Di solution, by providing more similarly-charged M-sites and a smaller volume. Exsolution of the excess Si as quartz (e.g. in Norway, Greenland and S. Africa) can create Al(iv) at lower T than if the CaTs proportion was in equilibrium with garnet.

The recent suggestion of O^- stability allows the not too remote possibility of new high-density supersilicic "pyroxene" end-members (e.g. $AS_2O^=_5O^-$, $D_{1.5}S_2O^=_5O^-$) at high P. Supersilicic pyroxenes are thus to be expected in Na-, Ca-, Al- & Si-rich systems at high P (blueschists, eclogites, experiments).

D22

GARNET AND CPX MEGACRYSTS FROM KASAI.

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Eastern Kasaï xeno-tuff breccia kimberlite include a long set of megacrysts:garnet,cpx ilmenite,rutile,kyanite, corundum,zircon and baddeleyite, Neither olivine nor enstatite have been found.We are only concerned with garnet and cpx. About 200 specimen each have been sampled from Mbuji Mayi and Tshibua pipes, eastern Kasaï.

All the garnets from Tshibua are Cr pyropes They tend to have relatively low Ca 0 contents (4.0 wt%)and Cr_2O_3 values in the range 0.95-6.5 wt% Two Cr pyropes show a particular zonation affecting only octahedral diadochic ions Al^{3+} and Cr^{3+}. All the cpx from Tshibua are diopsides. Except for one specimen the $Cr_2 O_3$ contents are below 0.9 Wt% and $Al_2 O_3$ values below 1.90 Wt%.Na_2O ranges between 1,40 and 2.0 wt%.Garnets and cpx from Tshibua are all ranged in the lherzolitic suite.

Several garnet and cpx megacrysts from Mbuji Mayi resemble those from Tshibua and are ranged in the lherzolitic suite yet an important part of analysed minerals are quite different. Cpx have considerable contents of Na_2O and Al_2O3 in the ranges 4-0-6.8 and 6,9-11.4 wt% respectively. Cr_2O3 contents do not exceed 0.2 wt%. These cpx are omphacitic, Some garnets belong to the pyrope-almandine-grossular serie. Both these latter minerals have been ranged in an eclogitic suite.

Using enstatite-diopside thermometers, the lherzolitic cpx show a possible equilibration range from 950 to 1350°C.Isotopic ratios $^{87}Sr/^{86}Sr$ of cpx are quite different of kimberlitic matrix, Garnet and cpx megacrysts show a reaction rim with the kimberlitic matrix, Thus a xenocristal origin is proposed for garnet and cpx megacrysts.

D23

Mg-ILMENITES IN ALKALI BASALTS FROM THE VOLCANIC HOGGAR AREA

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The Plio-Quaternary nephelinitic and basani-
tic volcanoes of the Tahalra area (Hoggar, south
Algeria) contain numerous upper mantle xenoliths
and xenocrysts (sp. lherzolite, pyroxenes and/or
amphiboles rich inclusions, kaersutite and fer-
risalite megacrysts). Mg-ilmenite have been
observed with a distinct habit in two types
of rocks :

* Large polycristalline xenoliths (3-20 cm)
which contain only Mg-ilmenite grains (0,03
to 15 mm) with exsolution of titanomagnetite
and Al-soinel. These xenoliths exhibit tectonic
fabrics which can be ascribed to solid state
flow followed by dynamic recrystallisation.
Their rounded surfaces display cavities filled
up with kaersutite, fassaïte and olivine. These
Mg-ilmenite xenoliths have the same chemistry
(25 to 37 % mol. of geikielite) and the same
texture as the Mg-ilmenites found in kimberlites
(a lack of outward Mg enrichment is the only
difference) (1).

* Lherzite xenoliths in which interstitial
undeformed Mg-ilmenite crystals (<2 mm) of iden-
tical composition are associated with kaersutite
(±olivine and fassaïte). From the study of a
composite lherzite-sp. lherzolite xenolith,
these nodules of Mg-ilmenite-lherzite are
thought to be pieces of veins which may occur
in the upper mantle lherzolites.

Textural relationships and chemical composi-
tions suggest a similar origin for these two
types of Mg-ilmenite. In both cases, they crys-
tallised from a liquid of high-Ti nephelinitic
composition in the upper mantle conditions.
Ascending later magmas sampled both deformed
and undeformed Mg-ilmenite xenoliths suggesting
either several generations or different tectonic
evolutions for the upper-mantle Mg-ilmenites.
(1) Contrib. Mineral. and Petrol.

D24

RELATIONSHIP BETWEEN GEOCHEMISTRY AND COLOR OF GARNET XENOCRYSTS FROM COLO-RADO-WYOMING KIMBERLITES

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Color of garnet grains obtained by alluvial
and(or) soil sampling programs may be a useful
indication of the presence of kimberlite in a
prospecting target area. Garnet xenocrysts
from 12 kimberlites in northern Colorado and
southern Wyoming were classified according to
color and chemistry in order to ascertain their
petrologic parentage and test the viability of
using grain color as a means of rapid identifi-
cation of kimberlite indicator garnets. Seven-
teen color groupings were established with the
aid of a G.S.A. Rock Color Chart, and grouped
into four major color categories: Group 5R
(red garnets), Group 5RP (red purple garnets),
Group 1OR (reddish-orange to reddish-brown
garnets), Group 5YR (brown garnets). Repre-
sentative samples of each color grouping have
been analysed by electron microprobe, and data
for 91 garnets reveals distinct chemical trends
between the major color categories. In general,
CaO and Cr_2O_3 increase whereas Al_2O_3 decreases
in order of Groups 5YR, 1OR, 5R, and 5RP, FeO
increases in order of groups 5R, 5RP, 1OR, and
5YR, and TiO_2 increases in order of Groups 5YR,
5R, 5RP, and 1OR. Groups 5R and 5RP have the
highest Cr/Al and lowest TiO_2, a "depleted"
chemistry typical of rounded pyrope xenocrysts
in kimberlite, Cr-rich garnet megacrysts, and

peridotite garnets. Groups 1OR and 5YR have
lower Cr/Al and higher TiO_2 and FeO, values
that are characteristic of garnets from webster-
ites, pyroxenites, eclogites, and granulites.
Some Group 1OR garnets have compositions similar
to Cr-poor garnet megacrysts. (Study supported
by Earth Sciences Section of NSF, Contract
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D25

THE SIGNIFICANCE OF SULFIDES IN SPINEL AND GARNET LHERZOLITES AS CARRIERS OF PLATI-NUM METALS

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Ultramafic nodules from alkali basalts and kim-
berlites are a major source for estimating the
chemical composition of the upper mantle. Concen-
trations of major elements and a large number of
trace elements are surprisingly uniform in primi-
tive nodules (1). Abundances of Ir and other noble
metals also show little variations in spinel lher-
zolites. However the content of,for example Ir in
these upper mantle samples is much higher than
that expected from core mantle equilibrium. Since
the relative abundances of Ir, Au etc. in these
samples are the same as those of undifferentiated
meteorites, it was suggested that these elements
are derived from a late meteoritic component at a
time when the core had already formed (1, 2, 3).
This hypothesis has been recently questioned by
Mitchell and Keays (4). These authors argued that
the siderophile elements in mantle samples are the
result of immiscible sulfide liquids, separated
from basaltic liquids formed by partial melting of
the mantle. Part of the evidence provided by Mit-
chell and Keays was the fact that only minor frac-
tions of Ir, Au etc. are contained in the major
minerals of upper mantle samples, and that there-
fore sulfides are the most likely host phases for
these elements.

We have separated and analyses sulfides from
spinel and garnet lherzolites. Preliminary results
have been reported (1). Two main questions will be
addressed in this investigation:
a.) Are sulfides the major host phase of noble me-
tals in upper mantle samples?
b.) What is the origin of these sulfides? Were the
noble metals originally contained in other phases
and did they partition into later formed sulfides?
We are planning to analyse these sulfides for lead
isotopes, in order shed light on their origin.
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D26

OPAQUE MINERALOGY AND CHEMISTRY OF IL-MENITE NODULES IN WEST AFRICA KIMBER-LITES: SUBSOLIDUS EQUILIBRATION AND CON-TROLS ON CRYSTALLIZATION TRENDS

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A regional survey of kimberlitic heavy mineral
concentrates from Liberia (2 pipes and 13 prob-
able dikes), Sierra Leone (3 pipes and 5 dikes),
Guinea (3 pipes) and Mali (3 pipes and 1 dike)

show that: (1) all are characterized by large concentrations of ilmenite ($Ilm \gg Gt \ggg Px$) with Mali>Liberia>Guinea>Sierra Leone; (2) Antoschka (Guinea) exhibits the largest variety of opaque minerals ($Ilm+Rut+Sp$); (3) Mali is characterized by low T anatase+Hem replacement of Ilm, and Sierra Leone has abundant sulfides ($Cpy+Po+Pn$) within Ilm; (4) extremely large (10-15 cms) Ilm are derived from Liberia; (5) Sierra Leone and isolated sites in Liberia have high MnO (16wt% max) contents in Ilm associated with calcite; (6) large variations and considerable overlap exist within and between kimberlite clusters in Ilm-Geik-Hem contents; (7) subsolidus reduction of Ilm to 2 $Ilm_{ss}+Sp_{ss}$ is unique to Sierra Leone whereas exsolution of Ilm_{ss} from Ilm-Geik-Hem_{ss} are restricted to Liberia and Antoschka; (8) Cr_2O_3-MgO variations are either tightly clustered along a parabolic curve delineated by $Mg_{Ilm} \lessgtr Mg_{sp}$ or dispersed within a broad hyperbolic envelope; (9) a coherent pattern of compositional variations is established between Ilm-Ilm_{ss} pairs which define a decompositional loop in the ternary Ilm-Geik-Hem that is consistent with experimental data at variable T-fO_2; and (10) by using the data from (9) and combined with Ilm compositions from southern Africa it is concluded that the dominant control on Ilm compositions is the T-fO_2 dependency of immiscibility within the system Ilm-Geik-Hem, such that Ilm-Hem_{ss} and Ilm-$Geik_{ss}$ are permissible, Geik-Hem_{ss} are absent, and intermediate (Ilm-Hem)-(Geik-Hem)$_{ss}$ are restrictive because $Sp_{ss}+(Pb+Kar+FPb)_{ss}$ is stable at low P.

D27

COMPLEX TITANATE COMPOUNDS (MO_2, M_2O_3, M_3O_5, M_4O_7, $M_{22}O_{38}$) IN KIMBERLITES: MINERAL REPOSITORIES FOR AND THE PARTITIONING OF LIL ELEMENTS.

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The mineralogy and genesis of components hosting large concentrations of (R) refractory (e.g., Cr,Nb,Ta,Zr) and LIL (e.g., K,Ba,Sr,REE) elements in kimberlites and kimberlite nodules provide insights to the nature of mantle reservoirs, may be used to impose constraints on degrees of partial melting, and may yield independent estimates of originating depths and sites of equilibration. R and LIL are abundant in rutile (MO_2), perovskite (M_2O_3), armalcolite-related (M_3O_5), zirconolite (M_4O_7), and crichtonite-related ($M_{22}O_{38}$) minerals. However, with the exception of MO_2(TiO_2 II) none of these compounds have established high P stabilities. It is proposed that substitution of Cr,Zr, and Nb into TiO_2 may be accomplished in compounds related to the high P parent structure αPbO_2 by

crystallographic shear (CS) comparable to those in the series $Mn O_{2n-1}$ - $Mn O_{3n-2}$ ($n=1,2,3$) and to $Cr_2Ti_{n-2}O_{2n-1}$ ($n=3,4,5$). Such compounds, on ascent-equilibration, yield a viable explanation for the occurrence of M_3O_5 (armalcolite type) in association with rutile and ilmenite, and for the ubiquitous presence of rutile and ilmenite intergrowths. Ba-K (Sr,Pb,Ca,REE) members of $M_{22}O_{38}$ compounds decompose to rutile+spinel+X....n phases suggestive of site occupation of LIL at high P into phases other than CS based structures. Using the model precursors of CS and non-CS structured compounds (i.e., αPbO_2 and $M_{22}O_{38}$) and constrasts in paragenesis, two distinct R + LIL evolutionary trends emerge: (a) in which Nb+Zr+Cr+K are complexed as high P incompatible liquid residua into MO_2, M_4O_7 ($Cr_2Ti_2O_7$) or $M_{22}O_{38}$ type compounds in nodules; and (b) low P melt residua in which Ti fractionates to form R-depleted ilmenite and a Ti+REE sink in perovskite at the terminal stages of kimberlite crystallization.

D28

A LAYERED DUNITE – WEHRLITE – WEBSTERITE FROM NEWLANDS, SOUTH AFRICA; EVIDENCE FOR SMALL SCALE FRACTIONAL CRYSTALLIZATION IN THE MANTLE.

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A layered mantle xenolith, LDN-10, has been found in the Newlands kimberlite. The bulk composition, calculated from modal mineral proportions, approximates a peridotitic Komatiite. The following layers are recognised: a) Dunite b) Wehrlite c) Gt-Wehrlite d) Gt-Websterite. Olivine and orthopyroxenes show minor chemical variations across the xenolith. The garnets and clinopyroxenes are strongly zoned, particularly with respect to Cr_2O_3, which also decreases systematically from the wehrlitic layers to the websteritic layer.

The layering in LDN-10 can be interpreted in terms of a fractional crystallisation model that is consistent with phase relations established for the CMAS tetrahedron (O'Hara, 1968). In this model, with a liquid corresponding to the bulk composition for LDN-10, the first mineral phase to crystallise will be olivine, followed by clinopyroxene, garnet and orthopyroxene respectively. This crystallisation sequence is reflected by the observed mineral assemblages in LDN-10 and is consistent with the observed Cr_2O_3 variation of both clinopyroxene and garnet.

Gurney et al (1975) proposed a fractional crystallisation model for the Matsoku xenolith suite. It is suggested that LDN-10 represents a similar type of mantle process, but on much smaller scale.

References:
Gurney J.J., Harte B., and Cox K.G. 1975: Phys. Chem. Earth 9, 507-523.
O'Hara M.J.,1968: Earth Sci.Rev. 4, 69-133.

(Late abstract)
MANTLE MINERAL ASSEMBLAGES AND PALAEOGEOTHERMS

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Many recent studies of the quenched mineral assemblages in magmas considered to have a deep mantle origin (alkali basalts and kimberlites) and their enclosed nodules, have sought to determine the depth at which the mineral geothermome-ters closed to further reequilibration. If the deduced P-T-points lie on a curve, then they are frequently interpreted to define the P-T-location of a palaeogeotherm. If the deduced P-T-points form an array, then uncertainties in P-T-calibra-

tion of a simplified chemical system (or the in-
herent problems in extrapolating from simple to
complex crystalline solutions) are introduced to
accommodate a desired palaeogeotherm. The hypo-
thetical "Kinked or perturbed" palaeogeotherms
have been straightened by some authors on grounds
of mineralogical problematics. Likewise, more re-
cent studies have shown that the deduced P-T-
equilibration conditions for sheared or unsheared
nodules are only mutually exclusive. Even if we
take the generous and pragmatic viewpoint that
deduced P-T-points from quenched magmas and their
nodules do not reflect reequilibration en-route
to the surface, we are still faced with the prob-
lem of what the nodules represent with reference
to the enclosing magma and whether the P-T-cond-
itions are anomalous in the long-term evolution
of the mantle.

We have attempted to use trace element and
other geochemical indicators together with con-
straint on mantle metamorphism and melting in a
framework governed by time-dependent convective
instability in the mantle, to consider, among
other characteristics, the age clustering of kim-
berlites (or their nodules, their location in
crustal fracture zones and the distinctly dif-
ferent depths of alkali basalt versus kimberlite
magma genesis.

Field trip in the Lesotho highlands after the Cape Town conference
Photo C. Froidevaux

E   Fluids in the mantle and metasomatism

E1

AN EXPERIMENTAL AND THEORETICAL ANALYSIS OF PARTIAL MELTING IN THE SYSTEM $KAlSiO_4$-CaO-MgO-SiO_2-CO_2 : A MODEL FOR ALKALIC MAGMA, CARBONATITE AND KIMBERLITE GENESIS.

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The introduction of dolomite as a solidus phase in carbonated peridotite compositions at 25-30 kb coincides with a rapid increase in CO_2 solubility over a small pressure interval (several kb) and a profound depression of the solidus temperature (200°C). Partial melt compositions through this interval change rapidly from a silicate melt (alkalic near the solidus) at low P to a carbonatitic melt where dolomite is introduced as a solidus phase and back to a silicate melt (haplokimberlitic) at still higher P. The details of these transitions are important to the genesis of alkalic magmas, carbonatites and kimberlites, but are obscured by the small P interval over which large changes in melt composition occur, by several solidus reactions which alter mineral assemblages (and thus melting reactions and melt compositions), and by the inability to rapidly quench and/or analyze partial melts generated by small degrees of partial melting. To understand better how the compositions of partial melts of carbonated peridotite change with increasing P, a combined experimental and theoretical analysis of melting relations involving Fo+Di+En+Carbonate+ Potassic phase (+CO_2) in the system $KAlSiO_4$-CaO-MgO-SiO_2-CO_2 has been undertaken to about 50 kb.

Partial melts in equilibrium with Fo+Di+En+Potassic phase+CO_2 show increasing CaO and MgO, at constant CaO/MgO=0.7 (wt), and decreasing K_2O, Al_2O_3 and SiO_2 with increasing P to about 25 kb; kalsilite component is stabilized while the diopside stability volume is depressed. Immediately above 25 kb, the CaO/MgO of partial melts increases to a value greater than 1 when dolomite is introduced as a solidus phase and the enstatite stability volume expands. Partial melts are never more MgO-rich than the kalsilite-dolomite-enstatite-CO_2 join at pressures below about 30 kb. At P>30 kb, K_2O contents are low (<4 wt%); in the absence of H_2O kalsilite is the stable and refractory potassic phase. An analysis of all possible reaction topologies generated by the intersection of melting reactions (both CO_2-saturated and CO_2-undersaturated) with the subsolidus reactions En+Mag=Fo+V and Di+Mag=En+Dol yield consistent conclusions: MgO and SiO_2 contents of partial melts increase and CaO, CO_2 and CaO/MgO decrease with increasing P.

Polybaric melt composition trends at P<25 kb mimic tabulated composition trends of strongly potassic, silica-undersaturated occurrences: Results of experiments in CaO-absent systems cannot duplicate the latter trends. The polybaric melt composition trend at P>30 kb ranges between calcite-rich and forsterite-rich extremes and is similar in this respect to differentiation trends for kimberlites. Melting reactions at the highest pressures considered in this study, involving dolomite and/or magnesite and peridotite minerals, can produce melt chemistries analogous to kimberlite compositions as cited in the literature.

E2

FUSION CURVES AND THE THERMODYNAMICS OF LIQUIDS TO HIGH PRESSURES

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Our determinations of anhydrous fusion curves of silicate and aluminosilicate minerals to high pressures reveal that marked structural and thermodynamic changes occur in the aluminosolicate liquids as functions of changing pressure and temperature. These changes prevent calculation of fusion curves from calorimetrically determined thermodynamic data; alternatively, thermodynamic data can be obtained from the fusion curves. Comparison of the solidi of albite with those of albite + quartz, sanidine, sanidine + quartz, anorthite, and diopside suggest that phase transformations in the crystalline phases have analogues in the liquids. This provides some basis for predicting the high-pressure structures of near-solidus liquids.

We have reinvestigated the systems quartz-H_2O-CO_2, albite-H_2O-CO_2, albite-H_2O, and albite-CO_2 to high pressures. These results permit calculation of activity coefficients for H_2O in the H_2O-CO_2 fluids. The albite-CO_2 solidus is the first determination of the effect of CO_2 on melting in an anhydrous, hydrogen-free environment, permitting us to determine the relationship between solubility and structure of the liquid.

Knowledge of the nature of deep-seated liquids will enable us to better understand phenomena such as magma genesis and the distribution of elements.

E3

OXYGEN FUGACITY AND THE FLUID C-H-0 PHASE IN THE EARTH'S MANTLE.

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From experimental work it is deduced that CO_2 reacts with mantle silicates above 26 kb to form carbonates. With pressures increasing still further dolomite or magnesite are buffering mixed fluid phases to continuously lower CO_2-activities.(Wyllie, 1978; Eggler,1978). In a similar way H_2O reacts to form hydrous phases - e.g. brucite- above about 90 kb, buffering the fluid phase to lower H_2O activities with increasing pressure. As a consequence a binary CO_2-H_2O phase will disappear as soon as a hydrous and a carbonate phase coexist with mantle silicates. (Ellis & Wyllie, 1979,1980)

The absence of carbonates from typical mantle

peridotites and the stable occurrence of dia-
mond indicate that oxygen fugacities must be
sufficiently low in the Earth's mantle to reduce
the CO_2 activity to a level below the stability
of carbonates.(Rosenhauer et al., 1977) Intrin-
sic oxygen fugacity measurements of mantle de-
rived samples indicate that fO_2 may be as low
as the wüstite-iron level.(Ulmer,1980; Arculus
& Delano,1980).

Thermodynamic calculations indicate that CH_4
is a stable species in a C-H-O fluid phase un-
der 90 kb and the corresponding temperature of
the mantle and fO_2 of the WI-buffer. It follows
that:

1. It is possible that a fluid phase with high
CH_4 concentrations is stable in the Earth's
mantle, and

2. The ultimate limit for the existence of a
fluid phase in a peridotitic mantle will be ex-
tended to greater depths by the formation of
methane.

E4

OXYGEN FUGACITES FROM THE ASSEMBLAGE OLIVINE-ORTHOPYROXENE-SPINEL

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Spinel co-existing with olivine and orthopyrox-
ene (ol-opx-sp) constitutes a widespread assemb-
lage in ultramafic rocks from many environments,
including upper mantle nodules in kimberlites and
alkali basalts. Through the equilibrium

$$6Fe_2SiO_4 + O_2 = 3Fe_2Si_2O_6 + 2Fe_3O_4 \qquad (1)$$

the assemblage may be used as a measure of oxygen
fugacity of these rocks. In practice all three
of the solid components in (1) are considerably
diluted in their respective phases, so that a
reasonable estimate of oxygen fugacity can only
be made if activity-composition relations of the
phases are accurately known. To this end a model
for spinel activity-composition relations has been
developed, which has been calibrated against exp-
erimental determinations of the activity of mag-
netite in the systems Fe_3O_4-$FeAl_2O_4$,Fe_3O_4-$FeCr_2O_4$
and Fe_3O_4-$FeAl_2O_4$-$FeCr_2O_4$. To confirm the applic-
ability of the model at high pressures and to sys-
tems which include MgO, a series of experiments
in a piston-cylinder apparatus have been perform-
ed at 1100°C and 30kb in the system MgO-Cr_2O_3
-SiO_2-Fe-H_2-O_2. An inner gold capsule contain-
ing ol+opx+sp+H_2O is run within a larger thicker
walled Au capsule containing an oxygen buffer
assemblage. The composition of the phases were
determined by electron microprobe analysis. That
equilibrium between the three phases is achieved
in both these experiments and in rocks may be
checked by comparing olivine-spinel and olivine-
orthopyroxene Fe^{2+}/Mg distribution coefficients.

The results show that nodules from kimberlites
equilibrated at oxygen fugacites between the iron-
wüstite and wüstite-magnetite buffers. Nodules
from alkali basalts show a rather wider range,
from below iron-wüstite (Calton Hill, Derbyshire,
England) to near nickel-nickel oxide (San Carlos,
Arizona, U.S.A.). These results broadly agree
with the intrinsic oxygen fugacity measurements.

E5

THE INSTRINSIC OXYGEN FUGACITES (fO_2's) of MEGACRYST ILMENITES FROM SOUTHERN AFRICA KIMBERLITES, TYPE A AND B SPINEL PERIDOTITES FROM SAN CARLOS, ARIZONA

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The oxidation state of the upper mantle and
magmas generated therein is crucial to our under-
standing of the origin and evolution of the core-
mantle-crust system. In a series of measurements
with O_2-specific electrolytes, we have shown that
a number of type A (or "chrome diopside" type)
spinel peridotites and spinel megacrysts are
close to iron wüstite (IW) in oxidation state.
In contrast, thermodynamic calculations suggest
that the intrinsic fO_2's of kimberlitic and alk-
alic magmas are close to the SiO_2-Fe_2SiO_4-Fe_3O_4
(QFM) buffer.

Homogeneous, cleansed megacryst ilmenites from
the Frank Smith, Excelsior and Sekameng kimber-
lite pipes display 1 bar intrinsic fO_2's ranging
from ≃0.5 log_{10} unit more oxidized than the Ni-
NiO (NNO) buffer to a close coincidence with QFM
over a temperature range of 950 - 1160°C. Des-
pite run durations >50 hours at 1150°C, no auto-
reduction of these or peridotite samples took
place. Fe_2O_3/FeO ranges from ≃0.32 to 0.71 and
MgO from ≃4 to 13 wt%. Assuming a cognate re-
lationship, these data suggest the kimberlite
host magmas are oxidized at depth, and contrast
strongly with our measurements on submarine
tholeiitic basalts from the Galapagos rift and
those of Sato (1972) on Hawaiian samples that
are close to IW.

Further evidence for strong contrast in intr-
insic fO_2's in upper mantle peridotite samples
is provided by studies of samples from San
Carlos. Type A peridotites are close to IW
whereas Type B's ("aluminous augite") are close
to NNO in the T range 950-1150°C. It is possible
that alkaline basalt types and metasomatized
peridotites may have a close genetic relation-
ship.

E6

AN EXPERIMENTAL STUDY OF THE ROLE OF CO_2 IN PHYSICAL PROCESSES IN THE MANTLE

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Kimberlite magma generation in the mantle is
linked to physical processes involving a fluid
phase which is likely to be CO_2-rich. In peri-
dotite xenoliths bubbles frequently occur within
olivine grains in association with spinel crys-
tals suggesting exsolution of a dissolved fluid
phase during ascent of the xenolith. Experiments
designed to clarify the role of CO_2 in bubble
development have been conducted in a Griggs appa-
ratus modified for high pressure. Hot-pressed
olivine samples were sealed in Pt capsules with
small amounts of silver oxalate, a material which
breaks down to CO_2 and silver at relatively low
temperature. The samples were held at p,T condi-
tions appropriate to the lower lithosphere for
periods of about a day. As expected from petrolo-
gic studies, a uniformly distributed carbonate
phase occurs along grain boundaries and as inclu-

sions within olivine. This is presumably magnesi-
te generated during: Forsterite + CO_2 Magnesite
+ Enstatite. By varying the p,T path followed
during quenching one can study either the degree
of incorporation of CO_2 into olivine under condi-
tions stabilizing the carbonate or the develop-
ment of features related to the generation of
free CO_2. Analysis of these samples is in pro-
gress. In addition, several samples have been
deformed and have developed shear zones contai-
ning mylonitic material. Thus application of
pressures up to 3.0 GPa has not precluded shear
zone formation.

E7
FLUID ACTIVITY IN THE MANTLE - EVIDENCE FROM LARGE LHERZOLITE XENOLITHS

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Lherzolite xenoliths in a breccia pipe from
northeastern N.S.W., Australia attain dia-
meters of up to 60 cm. They record, approx-
imately concentric with xenolith margins, zones
of alteration by hydrous and carbonic fluids
which may represent metasomatism by primary
mantle volatiles. Successive zones (each
about five cm. wide) decrease in alteration
intensity from the outside inward. The sim-
plified sequence of mineral assemblages is:
(1) quartz /talc/Mg-Fe-Ca carbonates, (2) talc/
Mg-Fe-Ca carbonates, (3) fresh spinel
lherzolites. Crosscutting this concentric
alteration pattern are discrete carbonate veins,
rarely radial with the xenolith shape, but
commonly en echelon.

The zonal nature of the alteration suggests
that fluid invasion occurred either (a) after
entrainment in the host basaltic liquid or
(2) within the mantle prior to entrainment
and possibly resulting from fluid activity
genetically linked with the production of the
host magma. If the major alteration event
took place in the mantle, this implies that
brecciation associated with volatile movement
can occur within the mantle. This may provide
a mechanism for xenolith entrainment which
commonly takes place within a vertically
limited horizon.

Abundant carbonate of light isotopic character
is present in the host basalt and may be of
primary mantle origin. This evidence of a
high CO_2 content may be significant in carry-
ing such large xenoliths to the surface.

E8
MAGNESITE AND OTHER MINERALS IN FLUID IN-CLUSIONS IN A LHERZOLITE XENOLITH FROM AN ALKALI BASALT

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Magnesite has been observed in CO_2-rich fluid
inclusions in a typical Cr-diopside and spinel-
bearing lherzolite recovered from the 1824 erup-
tion of Lanzarote volcano, Canary Islands. The
carbonate, which exists as 2-4 μm diameter cryst-
als on inclusion walls, was identified by its
rhombohedral form and electron beam-generated EDS

and WDS characteristic x-ray spectra in which C
and Mg are major elements. The carbonate occurs
as the sole phase in individual inclusions and
has only been found in those inclusions enclosed
in olivine. Phases present in other inclusions
in olivine include Fe-oxide (probably pure mag-
netite), Fe- and Cu-Fe-sulfides, and silica. Al-
though sulfides and magnetite may exist together
in the same inclusion, most magnetite-bearing
inclusions contain no other phases.

Regardless of the phases in them, mineral-bear-
ing inclusions tend to possess irregular shapes,
are relatively large (10-30 μm) and exist togeth-
er in arrays which define non-crystallographic
surfaces. These features distinguish them as a
group from all other inclusion populations in
which daughter minerals are absent.

The production of carbonate by reaction of ol-
ivine and CO_2-rich fluid requires only that CO_2
fugacities be sufficiently high for any set of
assumed conditions, i.e., the mere presence of
magnesite yields no information on the T and P
at which it formed. However, the apparent lack
of phases more siliceous than olivine, e.g., en-
statite or glass, in association with magnesite
(or magnetite) means that either olivine in the
immediate vicinity of the inclusion is non-
stoichiometric, or the carbonate crystallized in
a microfracture before annealing of olivine and
formation of the inclusion, presumably at mantle
P-T conditions.

E9
THE MINERALOGY, STRUCTURE AND MODE OF FORMATION OF KELYPHITE AND ASSOCIATED SUB-KELYPHITIC SURFACES ON PYROPE FROM KIMBERLITE.

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ca.

The mineralogy, structure and mode of formation
of kelyphite shells surrounding garnet is discus-
sed in relation to kimberlite emplacement. Pyrope
encrusted by kelyphite is commonly found in most
garnet peridotites, some eclogite xenoliths from
kimberlites, as well as a few garnet-bearing ser-
pentinites.Observations made with the aid of a
scanning electron miscroscope on 858 kelyphite-
encrusted garnet grains from 30 kimberlite occur-
rences and petrological examinations of kelyphi-
te rims enclosing garnet in ultrabasic nodules
from kimberlite are discussed.

Although the relative abundance of kelyphite-
encrusted garnet varies from one kimberlite to
another, kelyphite shells are most commonly de-
veloped on mauve garnets which are most probably
derived from peridotite and are least commonly
found on orange varieties from eclogites. The
underlying sub-kelyphitic surfaces formed on py-
rope as a result of kelyphitization are descri-
bed. There is a direct relationship between the
different types of surface features found on the
sub-kelyphitic surfaces and the structure and
mineralogy of the kelyphite shells surrounding
garnet and filling cracks within garnet.

During the ascent of kimberlite magma garnet
lherzolite nodules are moved upwards from depths
of approximately 150 km within the upper mantle
resulting in the kelyphitization of pyrope wi-
thin the peridotite nodules, forming shells con-
sisting of a spinel-two pyroxene assemblage. The
proposed zone of kelyphitization of pyrope lies
within the spinel lherzolite stability field and
is most likely to occur at temperatures of 900°C

to 1300°C and pressures of 10 kb to 25 kb within the upper mantle. The phlogopite-rich 'kelyphitic' material rimming garnets in eclogite xenoliths from kimberlite is considered to have formed in the region of the lower crust by the action of alkalies and volatiles associated with the hydrous phase of kimberlite emplacement.

(Preliminary Abstract)

E10
COARSE AND VEINED PERIDOTITES FROM N. TANZANIA TUFF CONES

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Lherzolite, harzburgite and wehrlite blocks from two Neogene tuff-rings in the Tanzania rift valley comprise olivine ($\underline{mg}$.93), enstatite, Cr-diopside ($Ca_{44}Mg_{52}Fe_4$, $Cr_2O_3$2.3., TiO_2,0.12) and chromite (MgO 13.1, Cr_2O_3 59.4 wt%); texture is coarse though strain and evidence of grain-boundary migration is common. Some blocks are cut by planar or anastomising veins of combinations of olivine ($\underline{mg}$.82), Ti-diopside ($Ca_{47}Mg_{45}Fe_8$, $Cr_2O_3$0.06, TiO_2 1.04%), Tiphlogopite ($TiO_2$4.18, Na_2O 1.14, $\underline{mg}$.83) Tipargasitic hornblende (TiO_2 3.5., $Al_2O_3$10.3, $\underline{mg}$.80) and magnesian ilmenite (mg O 13.1%). Compared with non-veined peridotite, in peridotite adjacent to veins the olivine is more Fe-rich ($\underline{mg}$.86 - .89) and cpx (being replaced by pargasitic hornblende) contains more Fe, Ti and Ca; the replacing amphibole contains less Ti, Fe, Al, K, and Ca, but more Mg and Cr, than vein amphibole. Bulk analysis of one vein resembles ugandite. Some non-veined peridotites also contain metasomatic mica and amphiboles and it appears some parts of the mantle below the Rift Valley are metasomatised and enriched in LIL-elements.

E11
DEPLETED MANTLE ROCKS AND METASOMATICALLY ALTERED PERIDOTITE INCLUSIONS IN TERTIARY BASALTS FROM THE HESSIAN DEPRESSION (NW-GERMANY)

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During Miocene basaltic magmas ranging from quartz tholeiites to melilite containing olivine nephelinites have been generated in the area north of the Vogelsberg volcanoe. They are exposed in about 2000 partly eroded necks, flows and beds of pyroclastics. About 73 percent of the basaltic coverage consists of alkali olivine basalts, about 12 percent of nepheline basanites and limburgites and 9 percent of olivine nephelinites. The majority of the latter species but less than 40 percent of the alkali olivine basalts contain spinel lherzolite and spinel harzburgite inclusions. At a few localities upper mantle rocks (spinel lherzolites, spinel harzburgites, griquaite and websterite) and xenoliths from the lower crust (granulites, pyriclasites etc) occur in pyroclastics.

The average modal composition of 30 equigranular lherzolite and harzburgite xenoliths is : 74 vol% olivine, 10 vol% orthopyroxene, 7 vol% clinopyroxene and 1-2 vol% spinel. Estimates of temperature of equilibration according the Wells geothermometer range from 870 to 1110°C for these samples. Spinels with 40 mol.% $MgCr_2O_4$ are stable up to about 30 kb at 1100°C (O'Neill, 1981). The abundant peridotites are depleted in numerous elements relative to the primary upper mantle composition. The primary upper mantle composition has been estimated by Wedepohl (1981) after redistribution of the compatible elements from the earth's crust into a 200 km mantle layer and of the incompatible and volatile elements into a 900 km mantle layer. Because of their abundance the depleted equigranular spinel peridotites are expected to represent large volumes of the upper mantle down to about 100 km depth.

Distinct indications of a metasomatic imprint on certain spinel lherzolites have been observed in several xenoliths from pyroclastics of our area. They are deformed into a fine grained

reequilibrated groundmass and coarse relics of olivine and orthopyroxene. These so called porphyroclastic spinel lherzolites usually contain a few percent phlogopite. Their fine grained groundmass has been equilibrated at temperatures from 800 to 1000°C (Wells geothermometer). Crustal granulite xenoliths from the same area have been equilibrated at temperatures from 800 to 900°C and indicate an origin from layers close to the Moho (32 km depth). Some coarse orthopyroxenes of porphyroclastic lherzolites contain exsolved clinopyroxene lamellae. Taking their bulk opx + cpx composition as the primary opx composition two stages of equilibration can be discriminated. The difference in temperature between the two stages ranges from 80 to 200°C (Sachtleben and Seck, 1981, opx-thermometer). Reequilibration is assumed to be due to diapiric uprise of mantle material. Phlogopite has been formed during or after reequilibration probably from metasomatic fluids.

E12
ULTRAMAFIC XENOLITHS FROM LAKE BULLEN MERRI AND MT. LEURA, S.E. AUSTRALIA, AND THEIR BEARING ON THE EVOLUTION OF THE CONTINENTAL UPPER MANTLE

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Some 48 ultramafic xenoliths from two neighbouring locations within the Newer Volcanics of Victoria, Australia have been investigated in terms of petrography, mineral chemistry and partly for bulk rock chemistry.

The xenoliths include lherzolites with and without hydrous phases (such as amphibole and phlogopite), wehrlites, pyroxenites, and hornblendites, and include cumulates and composite xenoliths.

Mineral chemistry provides evidence for equilibrium crystallization for individual nodules over a small range of depths (app. 45 km) but a range of temperature. Anhydrous assemblages yield temperatures of 1015 - 1065 C, phlogopite bearing assemblages yield 975 -1025 C and amphibole bearing assemblages yield temperatures of 820 - 1010 C with most in the 925 -975 C range.

Among the harzburgites and lherzolites there is a wide variation of MgO, CaO, Al_2O_3, and compatible elements, which can be modelled as an early partial melting event, giving rise to various degrees of depletion.

Amphiboles in lherzolites are developed independently and postdate the partial melting event, as a response to near-isochemical metamorphic reaction, consequent on addition of water. Possibly Na and K, but no Ti were mobile components during the hydration event. The relationships of incompatible elements to the partial melting event and the hydration remain uncertain.

The metasomatic (hydration) events predate but are not precursor conditions for production of basanite. Metasomatism is present in the uppermost mantle above the LVZ, but this is most probably not the region of formation of the alkaline magmas. The emplacement and passage of alkaline magmas through the lithosphere/upper mantle may be the cause of local metasomatism and of hydration.

Wehrlites, pyroxenites, some lherzolites and hornblendites are regarded as precipitates from magmas fractionating and/or crystallizing at mantle depths. Observable wallrock-reaction is extremely restricted (about 1 cm) as evidenced by composite xenoliths.

A liquidus phase diagram for a hydrous basanite provides constraints on precipitation at high pressures and offers an internally consistent model for the genesis of the wehrlite, pyroxenite and hornblendite suite.

E13
NATURE OF THE CONTINENTAL MANTLE BELOW THE GERONIMO VOLCANIC FIELD ARIZONA, U.S.A.

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Trace element and isotopic analysis of hydrous and anhydrous peridotites and their host lavas, from the Geronimo volcanic field Arizona, U.S.A., have helped compile a chronology of enrichment and depletion events in the mantle. Host lavas have low $^{87}Sr/^{86}Sr$ = 0.70289 - 0.70327 and uniformly high $^{143}Nd/^{144}Nd$ = 0.513021 - 0.513037. The time-integrated light REE depleted character of the basaltic source region requires some form

of enrichment to permit extraction of light REE enriched lavas at moderate degrees of melting.

Fragments of "veined mantle" have been analysed for REE, Nd and Sr isotopes. Co-existing kaersutite and diopside give an "age" of 169 ± 21 MA (1σ) (MSWD = 0.63) with an $(^{143}Nd/^{144}Nd)_I$ = 0.51287. Clinopyroxenes separated from five petrographically distinct peridotites exhibit an extreme range in $^{143}Nd/^{144}Nd$ = 0.512983 - 0.512603 and $^{87}Sr/^{86}Sr$ = 0.70272 - 0.704697, that overlaps the "mantle array". If the linear arrays on trace element and isotope diagrams represent "mixing lines" then we can define the enriched (E) and depleted (D) components in the mantle. First, the kaersutite veined Type I lherzolites from Geronimo and Dish Hill comprise a MORB residue (D) and an enriched component identical to Basin and Range lavas. Clearly kaersutite veins represent frozen conduits of basanitic magma. Second the anhydrous Type I and Type II lherzolites at Geronimo and San Carlos comprise a MORB residue (D) and an enriched component with $\Sigma_{Nd} \approx 0$. Mantle below the southwestern U.S.A. has experienced a multi-stage history comprising a major widespread depletion event (> 1 b.y.) and enrichment events caused by migration and infiltration of LIL element rich fluids. (Σ_{Nd} = 0 to 8.)

E14
MANTLE HETEROGENEITY : ISOTOPIC AND TRACE ELEMENT EVIDENCE FROM NUNIVAK ISLAND ALASKA

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A diverse suite of ultramafic and mafic nodules occurs in Quaternary basanites on Nunivak Island (166°W, 60°N), including granuloblastic-equant (GE), coarse-equant (CE), and coarse-tabular (CT) lherzolites, amphibole-pyroxenites, and pyroxene granulites. GE nodules have La/Yb ratios less than chondrites, and clinopyroxenes from these nodules have $^{87}Sr/^{86}Sr$ (0.70203-0.70264) and $^{143}Nd/^{144}Nd$ (0.51321-0.51330) ratios similar to those of oceanic-ridge basalts. We interpret these nodules to be petrogenetically related to oceanic-ridge basalts however, very low bulk rock K contents (9-17 ppm) complicate simple models. The CT and CE peridotites, some of which contain hydrous minerals, all have La/Yb ratios greater than chondrites, and have high concentrations of K (80-1065 ppm), Rb (0.058-2.83 ppm), Ba (3.7-42 ppm), and Sr (11-82 ppm) relative to the GE nodules (0.01-0.11 ppm Rb, 0.56-0.83 ppm Ba, 12-16 ppm Sr). These CE and CT nodules are similar to metasomatized peridotites from other localities. Isotopic data indicate that some of the amphibole-bearing peridotites ($^{87}Sr/^{86}Sr$= 0.70289-0.70313; clinopyroxene $^{143}Nd/^{144}Nd$ = 0.51309) are petrogenetically related to the amphibole-pyroxenites ($^{87}Sr/^{86}Sr$=0.70288-0.70297; 2 whole rocks $^{143}Nd/^{144}Nd$ = 0.51310). These pyroxenites have trace element characteristics consistent with an origin as crystal accumulates. We infer that this example of metasomatism is the result of the infiltration of a H-C-O-rich fluid and/or residual silicate melt which originated in the pyroxenites. Based on consideration of isotopic data, we concur with Menzies and Murthy (1980) that the metasomatism occurred recently, and that it is petrogenetically related to the basaltic volcanism on Nunivak. Metamorphic textures in the pyroxenites preclude a direct relationship with the host basalts.

E15
METASOMATISM AND CHEMICAL HETEROGENEITY IN THE SUB-CONTINENTAL MANTLE : Sr and Nd ISOTOPIC ANALYSIS OF APATITE RICH XENOLITHS AND ALKALINE MAGMAS FROM EASTERN AUSTRALIA

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Cenozoic volcanic rocks from E. Australia are relatively uncontaminated (viz. high Mg values, high Ni, Cr, Co and Sc) and offer a unique opportunity to study mantle isotopic heterogeneities. Most of the magmas in the S. Highlands province are geochemically distinct and reached the surface as isolated flows of limited volume. Consequently the considerable range in $^{87}Sr/^{86}Sr$ = 0.70289 - 0.70444 and $^{143}Nd/^{144}Nd$ = 0.512965 - 0.512611 (13 rocks) can best be reconciled by melt extraction from a geochemically and mineralogically inhomogeneous mantle. Trace element and isotopic analyses of Al-augite series xenoliths reveal the following: (1) Apatite-rich pyroxenites have a narrow $^{143}Nd/^{144}Nd$ = 0.51257 - 0.51266 and $^{87}Sr/^{86}Sr$ = 0.70368 - 0.70397, similar to that of the host rocks (i.e. $^{143}Nd/^{144}Nd$ = 0.512611 - 0.512663 and $^{87}Sr/^{86}Sr$ = 0.70405 - 0.70414). (2) Whole rock pyroxenites have slightly higher $^{87}Sr/^{86}Sr$ ratios than constituent minerals perhaps due to the presence of mica. (3) Minerals separated from the xenoliths (viz. apatite, amph. and cpx.) exhibit an extremely narrow range in $^{87}Sr/^{86}Sr$ = 0.703543 - 0.703665 and a wide range in $^{143}Nd/^{144}Nd$ = 0.51252 - 0.51276, with the exception of spinel which has a higher $^{87}Sr/^{86}Sr$ = 0.704139. The minerals and whole rocks plot to the left of the mantle array. (4) Co-existing spinel, apatite and clinopyroxene exhibit a narrow range in Sm/Nd that does not permit accurate dating of pyroxenite formation (~ 500 m.y.). The pyroxenites are believed to represent the products of infiltration and crystallisation of a kimberlitic liquid into the mantle. The mantle heterogeneities produced by such metasomatism may be widespread in the Southern Highlands and may explain the diverse nature of the volcanic rocks.

E16
Nd ISOTOPIC DISEQUILIBRIUM IN GARNET PERIDOTITES FROM THE BULTFONTEIN KIMBERLITE AND IMPLICATIONS FOR MANTLE METASOMATIC COMPONENT ADDITION

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The Sm-Nd and Rb-Sr isotopic systematics of garnet, diopside and phlogopite from coarse granular peridotite xenoliths in the southern African Bultfontein kimberlite pipe indicate addition of a mantle metasomatic component. $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios of garnet, diopside and phlogopite (major REE carrier phases), corrected back to the time of kimberlite emplacement (90 m.y.), are negatively correlated precluding conventional Nd isochron relationships and requiring exotic component addition without reequilibration. On a Nd-Sr correlation diagram these phases lie on an extension of the mantle array defined by mantle derived volcanics, at lower Nd and higher Sr isotopic ratios, as pre-

viously demonstrated for a suite of Bultfontein diopsides (Menzies & Murthy, 1980). Pipe emplacement initial $^{143}Nd/^{144}Nd$ ratios decrease in the sequence phlogopite-diopside-garnet such that garnet lies furthest into the "enriched" quadrant. Identification of one or more of these phases as representative of the metasomatic component is complicated by the complex histories of the host peridotites, which appear to have included previous melt extraction. If phlogopite (diopside) is metasomatic, then its source evolved with a higher Sm/Nd ratio than the host garnet harzburgite. This seems counterintuitive given the conventional high Sm/Nd ratios of garnet and is the subject of further investigation.

E17

ZONED MINERALS IN PERIDOTITE NODULES: CLUES TO MANTLE DYNAMICS

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Compositional zoning within peridotite phases has been measured by electron probe microanalysis in order both to constrain rates of pressure and temperature change and metasomatism in mantle peridotite and to infer relative cation mobilities in the mantle. Rocks studied include garnet-inclusion pairs from ultramafic diatremes on the Colorado Plateau, composite peridotite nodules from Kilbourne Hole, and garnet lherzolite nodules from The Thumb, a minette diatreme on the Colorado Plateau.

Results from garnet lherzolite nodules from The Thumb document metasomatism and constrain its timing. Calculated temperatures for sheared and coarse nodules are mostly in the range 1050-1400° C. Garnets in two sheared nodules have rims enriched in Fe, Ti, and Na and depleted in Mg relative to grain cores. Olivine and diopside inclusions in garnet are enriched in Mg and Cr and depleted in Na, Ti, and Fe relative to matrix phases. Matrix pyroxenes homogenized distinctly faster than garnet. Ti mobility in garnet was less than those of Fe and Mg by about a factor of 4. Our data support the earlier hypothesis that these sheared nodules formed by deformation and metasomatism of coarse peridotite. Garnets in two coarse peridotites, however, are also zoned, so deformation and metasomatism are not necessarily related. Several

nodules with zoned garnets have relatively flat normalized REE patterns, and there is no evidence that the Fe-Ti metasomatism was accompanied by LREE enrichment. Comparison of observed and calculated diffusion gradients suggests metasomatism occurred within a short period (perhaps tens of years) before minette eruption.

E18

KIMBERLITE: «THE MANTLE SAMPLE» FORMED BY ULTRAMETASOMATISM

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Even with optimum general mantle compositions and regardless of the mechanism of melt generation, a kimberlite melt fraction would be minute. Melt segregation to give localised eruption, exploiting pre-existing zones of weakness, poses insuperable problems for mechanisms of pervasive melt generation that are favoured for other types of magmatism. Neither diapiric, nor "hotplate" melting could suffice because any initial melt would be intergranular and extremely diffuse.

Experiments indicate that the kimberlite solidus inflects to a positive dP/dT between 100 and 200 km deep. Diatremic kimberlite activity is consistent with flashover eruption from the near-solidus and can originate only near the inflection, or at shallower levels. Ascent of kimberlite melt from greater depths would mean upward departure from the solidus and hence vapour undersaturation. This is the unavoidable path of deep diapirs, which would never provide the activity in its observed form. Xenolith PT trajectories, of all ages and from all cratons, are in grazing incidence with the inflection zone, indicating its critical nature, and adding to the case against rising diapirs.

Stockwork metasomatism represents a plausible alternative. It concentrates the incompatibles in linked channelways prior to melting, and eliminates the need for segregation after melting of liquid traces from a large mantle volume. The channelway extensions to the surface form the guides to kimberlite eruption once the stage of ultrametasomatism/melting is achieved.

(Late abstract)
CONTRASTING TYPES OF MANTLE METASOMATISM

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Within the past decade, metasomatism of upper mantle peridotites has been increasingly invoked to account for major element, trace element and isotopic inhomegeneities in the upper mantle and to create source areas for volcanic rocks whose geochemical properties would be otherwise difficult to explain.

Two major types of metasomatism can be recognised:-

(1) Patent metasomatism in which textural replacement of primary phases by later generally-hydrous phases is evident.

This has been recognised in kimberlite and basaltic xenolith suites and includes replacement of garnet, clinopyroxenes and orthopyroxene by amphibole and/or phlogopite. In some specimens this metasomatism is clearly related to recognisable veins or zones comprising phases rich in K, Na, Rb, Ti, Nb etc., whilst in other specimens the metasomatism is pervasive on the hand-specimen scale. A more subtle type of patent metasomatism has been recently recognised in peridotite xenoliths from S. Africa

and Tanzania in which clinopyroxene is replaced by orthopyroxene (±phlogopite and ilmenite); this is most logically explained by CO_2 flushing. In the xenolith suites from kimberlites and K-rich volcanics, K-metasomatism appears dominant, whilst in basaltic suites, Na-metasomatism is the more common; the chemistry of the host igneous rocks appears to mirror the dominant type of metasomatism. In the case of K-metasomatism of kimberlite suites xenoliths from S. Africa, the enrichment event has been placed at 150 - 200 m.y. (Erlank and Shimizu, 1977, Kramers et al., in prep.).

(2) <u>Cryptic metasomatism</u> is a less obvious form of metasomatism, being only revealed by comparison of major and minor element chemistry with Sr-isotope and REE chemistry. A major depletion event has depleted mantle xenoliths in "basaltic" components such as Al_2O_3, FeO, CaO and Na_2O, but upon this has been imposed an event during which the earlier refractory rocks (component A) were enriched in K, Rb light REE, and U (component B); although differing in detail, this depletion/enrichment pattern has been recognized in the granular peridotite xenolith suites in kimberlites and basaltic hosts from S. Africa, Tanzania Australia and western U.S.A. Of particular importance is the dating. This enrichment event at Lashaine, Tanzania, is dated at 2.0 b.y., and a further (calculated) age for an enriched event in the S. African mantle is at ∿ 1500 m.y. Hence it appears that some areas of upper mantle have been subjected to 2 enrichment events - one ancient, the other quite recent in geological terms.

The Navajo field trip : nodule hunting
Photo C. Froidevaux

F Crust-mantle transition

F1

THE NATURE OF THE LOWER CRUST/UPPER MANTLE TRANSITION IN EASTERN AUSTRALIA – EVIDENCE FROM ECLOGITE AND GRANULITE XENOLITHS IN BASALTIC ROCKS

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Lower crustal xenoliths occurring in basaltic rocks range from garnet-bearing granulites and eclogites, through pyroxenites, amphibole-rich metagabbros to felsic metamorphic rocks. Contact relationships between different rock types suggest a complex petrogenesis including multiple intrusive, metasomatic and metamorphic events. Unaltered spinel therzolite, typical of "normal" eastern Australian upper mantle, is interleaved with or veined by eclogitic and granulitic rocks. Geobarometry using a variety of methods yields equilibration pressures for different xenoliths ranging from 12-18 kb. Geothermometry gives ranges of different xenoliths from 850° to 950°c. These physical parameters suggest the eastern Australian crust may be up to 60 km thick and has sustained a high geothermal gradient.

The nature of the mineral assemblages and the contact relationships suggest that the Moho is not a discrete feature, but is represented by a transition zone over approximately 20 km. This is in agreement with geophysical parameters (mainly seismic velocities) determined for this region.

The geochemistry of the lower crustal xenoliths suggests they originated as underplating of the crust by continental-type basaltic magmas. It is postulated that such addition of basaltic magma to the lower crust may represent an important alternative or additional mechanism to the conventional andesite model for crustal accretion.

F2

PERIDOTITE NODULES FROM THE NOGPETSEU AND LIPELANENG KIMBERLITES, LESOTHO: A CRUSTAL OR MANTLE ORIGIN.

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Observed variations in both whole rock and mineral chemistries have lead to the recognition of four groups of peridotite nodule samples in these kimberlites, which overall contain an unusually high proportion of spinel bearing garnet free peridotites. Equilibration temperatures estimated from various mineral equilibria, together with general geochemical considerations, strongly suggest that Group 1 (dunitic spinel wehrlite/lherzolite) and Group 2 (more 'fertile' spinel lherzolite) nodules are of lower crustal origin. However, Group 3 ('depleted' spinel lherzolite/harzburgite) and Group 4 ('depleted' garnet harzburgite) nodules are considered to have had progressively deeper upper mantle origins. The implication is therefore of a Cr-spinel

(Y_{Cr}^{Sp} = 0.25-0.48) peridotite zone at the top of the mantle section sampled by these kimberlites. Such rocks mostly show subsolidus deformation and recrystallisation effects leading to the development of mosaic and symplektite textures. Element partition considerations indicate that such textures have developed during cooling from an earlier temperature maximum.

F3

MANTLE AND LOWER CRUSTAL XENOLITHS FROM KIMBERLITES OF THE CENTRAL CAPE PROVINCE, R.S.A.

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In the central Cape Province Cretaceous-age kimberlites are intruded on a regional scale through postulated Namaqua mobile belt basement (1000 m.y.), that forms the southern fringes to the Kaapvaal craton. These kimberlites are non-diamondiferous. Mantle-derived peridotite and pyroxenite xenoliths are found together with lower crustal eclogites and garnet granulites in these kimberlites. The peridotites are inferred to have equilibrated at lower P,T's than similar xenoliths in kimberlites of the Kaapvaal craton. The lower crustal suite is believed to have equilibrated during high grade metamorphism accompanying Namaqua tectogenesis. Geochemical data are presented for the different xenolith suites.

F4

Nd- AND Sr-ISOTOPE STUDIES ON CRUSTAL XE-NOLITHS FROM SOUTHERN AFRICA

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The presence of crustal xenoliths in kimberlite pipes across much of southern Africa offers a unique opportunity to determine the horizontal, and, in some areas, the vertical dimensions of segments of continental crust of different ages. Particular questions include the balance between new and reworked crustal material in the Proterozoic mobile belts, whether the Archaean cratonic nucleii are underplated by a younger lower crust, and possible relationships between stabilisation of the crust and events in the uppermost continental mantle.

Ten samples of predominantly basic granulites from Lesotho kimberlites scatter about a whole rock Sm-Nd errorchron corresponding to an age of $1.4 \pm .1$ Ga, with an initial $^{143}Nd/^{144}Nd$ ratio slightly higher than CHUR at that time. The remaining five samples plot above that errorchron suggesting that they either represent younger material, or they were derived from a more depleted source region. In either case 1.4 Ga is the best estimate for the maximum age of the lower crust beneath Lesotho. Granite- and paragneiss xenoliths from Kimberley and two granulite facies metasediments from near Kroonstadt yield model Nd (T_{CHUR}^{Nd}) ages of 2.9-2.4 Ga, consistent with their position on the Archaean craton. However, seven of the eight samples analysed of both upper and lower crustal material from pipes in the Namagua Mobile Belt have Proterozoic model Nd ages (1.0-1.5 Ga) and only one contains any indication of a longer crustal residence time. The available evidence suggests that a considerable volume of new crust was generated in the Late Proterozoic, and that upper mantle heterogeneities of that age were subsequently sampled both by Karoo magmatism and kimberlite emplacement.

F5

BASAL CRUST (?) FROM LASHAINE, E. AFRICA.

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Detailed petrographic and mineralogical studies of a suite of basic garnet-plagioclase-clinopyroxenites, websterites and garnet anorthosite,
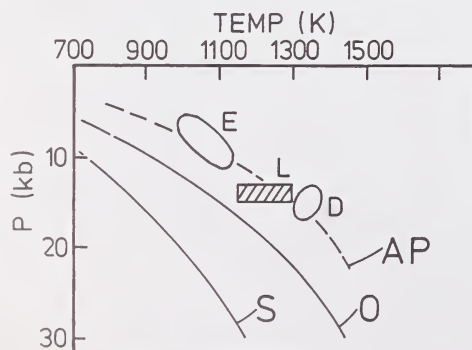
indicate equilibration under P-T conditions of 1150-1300 K and 1.3-1.5 GPa. Within the uncertainties of the thermometers and barometers, all of the xenoliths may have come from the same restricted zone in the lithosphere; resembling a suite of olivine-normative metagabbros. The pressure estimates are consistent with the presence of kyanite needles in every sample bearing plagioclase, and indicate derivation from the deepest parts of the crust; assumed to be 35-40 km in this part of Africa.

The calculated temperature (1200 K) for the Lashaine granulites lies well above temperatures at ~1.4 GPa predicted from a standard shield (S) geotherm (850 K) and even an oceanic (0) geotherm (1060 K). A new "alkaline province" (AP) geotherm is proposed, based on well constrained P-T estimates for granulite xenoliths from Delegate (D), Engeln (E) and Lashaine (L).

F6

LOWER CRUSTAL XENOLITHS FROM COLORADO-WYOMING STATE LINE KIMBERLITES

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Granulite facies xenoliths recovered from kimberlite in the state line district of northern Colorado and southern Wyoming are primarily anorthosite, leuconorite, norite, gabbronorite, hypersthene, granulite, two pyroxene granulite, two pyroxene garnet granulite, and clinopyroxene garnet granulite. No known granulite facies rocks are exposed in this area and the entire nodule population is interpreted as lower crustal in origin. The most abundant groups of lower crustal xenoliths are mafic garnet granulites in which allotriomorphic granular and cumulate textures are obscured by symplectites and coronas produced by late subsolidus reactions and exsolution. Continuous modal variation occurs between the garnet granulites and garnet clinopyroxenite or eclogite as orthopyroxene and plagioclase are eliminated.

Garnet-clinopyroxene equilibration temperatures of 570 - 690°C were obtained for the garnet granulites using the method of Raheim and Green (1974). Based on experimental work of Green and Ringwood (1972), equilibration pressures for the garnet granulites are estimated to fall in a range of 10-18 Kb. suggesting depths of approximately 30-55 km. Normative compositions of the mafic granulites are mostly equivalent to quartz tholeiite and olivine tholeiite. The mineralogy of the nodule suite suggests that the lower crust in the Colorado-Wyoming state line region is a predominantly mafic igneous-metamorphic complex. (Study supported by Earth Sciences Section of NSF, Contract EAR-7810775)

F7

THE IVREA ZONE, AN EXAMPLE OF THE EVOLUTION OF DEEP CONTINENTAL CRUST

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Seismic and gravimetric studies have shown that the MOHO-discontinuity rises from a depth of about 30 km up to 3 km in the Ivrea

zone region (e.g.Berckhemer 1968), giving us the opportunity to study a segment of deepest continental crust. The Ivrea zone consists mainly of amphibolite to granulite facies pelitic and mafic rocks. Spinel-peridotites are restricted to the highest grade part adjacent to the Insubric Line. The peak of metamorphism is considered to be due to the advective heat associated with these mafic-ultramafic intrusions. The metapelites show a considerable amount of partial melting and the so-called stronalithes (=granulite facies metapelites) are regarded as restites produced by "degranitization" of the metapelites (Schmid 1978). Rb-Sr determinations on restites and neosome, 30-50kg samples, give a 478+20 m.y. age, dating approximatly the peak of metamorphism (Hunziker and Zingg 1980). During this thermal event at least two phases of deformation can be discerned. Subsequent, cooling was very slow ($\leqslant 2^{\circ}C/m.y.$) and high-T conditions lasted into Hercynian time as can be demonstrated in the phlogopite-peridotite of Finero (Hunziker and others, this conference). During this period of slow cooling, few retrograde, discontinuos reactions occur. However considerable retrograde cation exchange between neighbouring mineral grains is observed. Using T-estimates, the end of this retrograde cation exchange might be correlated with Rb-Sr data. Band isochrons yielding ages of approximately 350 m.y. give the end of Sr exchange at the cm scale.

F8

EMPLACEMENT AND CRUSTAL CONTAMINATION OF THE PERIDOTITES IN THE IVREA-ZONE

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Based on structural work combined with Rb-Sr, K-Ar, as well as main and trace element analysis on basic and ultrabasic rocks of the Ivrea zone, a multistage emplacement history of the peridotites must be postulated. A first granulite facies episode with at least 3 deformation phases is followed by a second amphibolite facies episode ending with a mylonisation; followed by a third episode of green schist facies deformation of presumably Alpine age.
Structural work shows that the peridotites already underwent a first deformation of lower Paleozoic age under granulite facies conditions, together with the surrounding metapelites. 2 different peridotites occuring in one and the same body can be distinguished. Hornblende peridotites and the different peridotites containing no phlogopite are characterized by low $^{87}Sr/^{86}Sr$ initial values around .7025 -.7035. (The same low87/86 ratios are found for the cogenetic gabbros), by Rb/Sr ratios lower than .02 and by high K/Rb ratios above 1000. On the other hand phlogopite peridotites have crustal Rb/Sr ratios between .2 and 2.0 and crustal K/Rb ratios around 250. These rocks revealed a Rb-Sr whole rock isochron with an age of 305± 10 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of .7062±5 (cogenetic gabbros show even higher Sr ratios). The analytical data of the phlogopite peridotite so far point to a crustal contamination, that according to structural criteria must have taken place at the end of the granulite facies episode.
Combining our Rb/Sr data on ohlogopites as well as whole rocks, we can extrapolate from the present day

$^{87}Sr/^{86}Sr$ ratio of the phlogopites over the initial ratio of the peridotite isochron 305 m.y. ago to the assumed Sr evolution curve of the mantle and the intersection of the two evolution curves, marks the time of the Sr contamination around 350 m.y. ago. This time mark coincides with the end of the small scale Sr homogenisation in the surrounding metapelites.

F9

PRE-ALPINE AMPHIBOLITE-FACIES METAMORPHISM IN SHEARED GABBROS OF THE ULTRAMAFIC LANZO MASSIF (INTERNAL WESTERN ALPS)

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The Lanzo Massif, one of the largest ultramafic bodies of the Alps, consists of a spinel/plagioclase lherzolitic core, with minor harzburgite and dunite, surrounded by serpentinized lherzolite and antigorite serpentinite (1). This massif, commonly considered as deriving from the upper mantle originally underlying the Insubric Plate, is now considered, due to the discovery of widespread early-Alpine H-P eclogitic parageneses, as part of the Western Alps ophiolitic belt (2). Within the peridotitic core, besides the well described gabbro and diabase dykes (3), a special type of mylonitic gabbro has been found, which is characterized by the presence of dark brown hornblende. The gabbro shows a polyphase pattern of HT deformation, and consists of olivine, clinopyroxene, orthopyroxene, plagioclase, ilmenite, apatite and brown hornblende (kaersutite to Mg-hornblende). Locally plagioclase is converted to jadeitic pyroxene + zoisite + quartz assemblage. Reconnaissance K-Ar dating was attempted on brown hornblende separates from the mylonitic bands. The apparent ages obtained range from 440 m.y. to 1650 m.y. and are most probably due to variable amounts of excess 40 Ar. The data do not fit on an isochron and no reliable age for the hornblendes can therefore be calculated. It is interesting to note that model Sm-Nd and Rb-Sr ages for Lanzo (4) fall in the same range. New dating experiments are needed to solve this problem.

Refs.: (1) NICOLAS, Thesis, Nantes, 299 p., 1966; (2) COMPAGNONI & SANDRONE, Rend. S.I.M.P., 35, 842, 1979; (3) BOUDIER, Thesis, Nantes, 163 p., 1976; (4) RICHARD & ALLEGRE, E.P.S.L., 47, 65-74, 1980.

F10

OROGENIC LHERZOLITES AS WITNESS OF MANTLE CONVECTION

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Orogenic lherzolite bodies are key places to study mantle heterogeneities and to try to understand these heterogeneities, as it is possible to have indications about geometric position of one sample compared to one another.
Our study has been done on the massif of Lherz (France), Beni Bousera (Morocco) and Lanzo (Alps).
Our results show important isotopic heterogeneities on the initial $^{87}Sr/^{86}Sr$ ratios of the lherzolites, even at small scale.
These heterogeneities are comparable to the one found on MORB.

All these observations coupled with Rb-Sr and REE data on whole rocks lead us to suppose that before being emplaced as orogenic lherzolite bodies,the mantle piece suffered a very complex geodynamic cycle where lherzolite suffer successive light partial melting events. Pyroxenites are created at different stades.

Thus, in the same mantle part are regrouped ultramafic and mafic rocks which were isotopically homogenized at different ages.

To decipher the history the only way is to date with Sm-Nd chronometers different kinds of mafic layers. This has been attempted. The preliminary results we have concern the last mafic layers created in the massifs : garnet clinopyroxenites in Beni Bousera, and gabbros in Lanzo. They give new informations about the tectonic emplacement of the lherzolite body.

F11
XENOLITHS OF PERIDOTITE, PYROXENITE AND ECLOGITE IN GRANULITE ROCKS OF PRE-HERCYNIAN UPPER MANTLE AND LOWER CRUST IN THE EASTERN BOHEMIAN MASSIF (CZECHOSLOVAKIA)

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Garnet peridotites, peridotites, pyroxenites, and several types of eclogites form inclusions in pre-Hercynian garnet-kyanite ($\pm$ opx) granulites. Mineral assemblages of inclusions, structural position and distinct reaction rims show that the xenoliths have been incorporated in the parental rocks of granulite before the metamorphic foliation took place.

The element distribution between garnet, orthopyroxen, clinopyroxen indicate relict temperatures and pressures corresponding to the upper mantle and lower crust conditions. Some of the inclusions however are of crustal derivation and exhibit the mineralogy corresponding to the upper crust.

F12
CRUSTAL SINKING OF THE ALMKLOVDALEN GARNET LHERZOLITE BODY (NORWAY)

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The Almklovdalen ultramafic body included in the Basal Gneiss of Southern Norway is composed mainly of amphibolitized/chloritized harzburgite and dunite with cores of layered garnet lherzolite.

Parageneses show a retrograde evolution starting in upper mantle conditions : P = 17-28 kb, T = 645-820 C (fixed by Medaris, 1980), and evolving in lower crust hydrated conditions to P 7kb, T = 650-700 C.
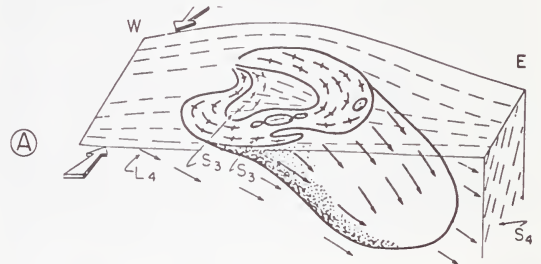
Structures and microstructures indicate a continuum of deformation related with the paragenetic evolution, developed during the Svecofennian cycle (1400-1700 Ma).

Microstructural study emphasizes the role of fluids in favoring annealing of textures and enlarging the field of "low temperature" slip system in olivine.

Structural study related with gravity data suggest a geometry of "inverse diapir" (figure) developed by gravity sinking, during this evolution in lower crust conditions.

G

Geodynamics and magma genesis

G1

THE ROLE OF KIMBERLITE IN MANTLE EVOLUTION

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Kimberlite (KIMB) appears to play a role in mantle evolution similar to KREEP in the Moon. It is enriched in all the trace elements except for those which are retained by garnet and clinopyroxene. Enriched magmas can be viewed as a mixture of MORB plus KIMB. KIMB may be a late stage residual fluid of a crystallizing eclogite cumulate. The ratio of trace element concentrations in MORB to those in KIMB equals the solid/liquid partition coefficient for an eclogite residue, implying that the MORB source was depleted by removal of a kimberlite-like fluid. A primitive mantle pattern can be approximated by a mix of 25 MORB: 1 KIMB. This gives a flat terrestrial pattern for the LIL and an enrichment of about 10. This implies that the depleted and enriched reservoirs (including continental crust) result from about 10% melting of primitive mantle. The melt forms a series of cumulate layers. KIMB forms from the final 4% melt fraction of the eclogite cumulate.

If MORB is formed by extensive melting of eclogite, diapirs must be able to ascend from great depth without appreciable fractionation. The physics of diapiric ascent is reviewed.

G2

DIAPIRISM AND MAGMA GENESIS : AN INSTABILITY ANALYSIS.

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Among the different hypotheses proposed for magma generation, the mantle diapir certainly is one of the most popular (and may be the most plausible).

We have investigated the problem of the behavior of a piece of mantle subject to partial melting. The problem can be described by two coupled non linear equations. One for the heat budjet, one for the momentum.

The discussion of the momentum equation shows the need of a process which lowers the viscosity around the diapir by a factor 10^5 to obtain a rising effect. We adopt the hypothesis of Anderson's halos.

Using this effect as a working hypothesis, we discuss the differential system in a phase space (velocity, temperature difference with surrounding).

The discussion shows clearly the existence of a zone where the diapir is stable and a zone where both velocity and degree of partial melting increase with time.

A more complex case which involves gaz bubbles is also discussed.

G3

MECHANICAL ASPECTS OF CONTINENTAL RIFTING

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Continental rifting is associated with characteristic shallow features like extension, vertical movements and deep seated phenomena as thinning of the lithosphere and upwelling of mantle material. This findes expression in anomalous data of : heat flow, gravity, seismic wave velocities as well as the occurence of volcanic activity.

Several attempts of concepts for mechanisms of rifting are discussed on the base of quantitative models. In particular plate collision as well as plate bending at hot spots fail to serve as a self supporting mechanism of rifting, because it is unlikely on mechanical grounds to transmit the necessary energy over the required distances. Lithospheric stretching has been reported to be a nonsufficient mechanism on the base of geothermal arguments.

Models on a mantle diapir concept are considered in detail according to the initial and diapir phase of development and the induced stress regime in the subsurface region in addition. Thereafter the typical wavelength across continental rifts requires the existence of a distinct crustal layer. Even at low amplitude level the developing ascent of mantle material affects the topic layer of diapiric

uprise meet the deduced course of data based gradients.

The highest rate of diapir uprise coincides with the maximum of crustal extension which is however confined to a narrow zone. The extensive stress regime becomes drastically altered by induced structural changes at the crust mantle boundary imposing mass excess. This leads in case to substantial decrease of the amount of extensive stresses up to a possible change of the regime to compression. Such conditions are related to a development towards the so called fossile graben type beneath basins.

The evolution and the development of enlongated mantle diapirs is finally the only concept which accounts for an optimum number of phanomena associated with continental rifting.

G4

HIGH TEMPERATURE PERIDOTITE INTRUSIVE INTO AN EVAPORITE SEQUENCE, ZABARGAD, EGYPT.

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The island of Zabargad (St. John's) is an uplifted fragment of Red Sea lithosphere which contains upper mantle peridotites. Zabargad is famous for large (up to 10cm) faceted crystals of peridot. The island contains three peridotite bodies, the largest of which is young and associated with the ocean rift. This body was intruded at high temperatures into an evaporite sequence which underlies the Red Sea. The sediments contained marly, calcareous, argillitic and mainly evaporite units which were high temperature contact metamorphosed into dark pelitic-carbonatitic rocks and light colored clastic rocks. Hornfelsic rocks are common and contain quartz, scapolite, phlogopite, tremolitic hornblende and albite, in varying proportions. One unusal assemblage near the contact contains cordierite, enstatite (En 99.9), phlogopite and rutile; cordierite is up to 4cm, enstatite to 2cm. Cordierite cores are surrounded by indialite rims and the assemblage is one of high temperature crystallization and rapid cooling in a Mg-metasomatic environment. The peridotite is mainly fresh uniform (Fo 90-93) spinel lherzolite and harzburgite; some is plagioclase-bearing. Hornblende-bearing lherzolites are probably the result of upper mantle metasomatic processes. Peridot is found in dike-like units which consist nearly entirely of olivine with minor Ni-rich serpentine and Fe-Ni oxide. The peridot is found in open cavities and as overgrowths on large (up to 20cm) flat brown olivine crystals. Peridot is also Fo 90-93 and has abundant fluid inclusions which Clocchiatti et al. (1981) find to be remarkably hypersaline; they formed at high temperatures (750-900º). Peridot was formed by magnesian hydrothermal solutions which are to be expected in young oceanic rifts.

G5

THERMAL HISTORY OF PORPHYROCLASTS AS EVIDENCE FOR MANTLE DIAPIRISM UNDERNEATH THE WEST EIFEL (WEST GERMANY)

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Porphyroclastic mantle peridotites of the NW end of the West Eifel volcanic chain contain orthopyroxenes up to 8 x 2.5 mm in size. Clinopyroxenes and spinels have unmixed in the center of the opx. Core compositions of the opx-porphyroclasts before unmixing were obtained by microprobe analysis with a defocused beam integrating over the unmixed phases. Temperatures derived from the reconstructed core compositions are similar to the high temperature coarse grained peridotites from the center of the West Eifel, i.e. ~1100ºC. For the rims of the porphyroclasts and pairs of opx-cpx neoblasts temperatures of about 800ºC were calculated. The porphyroclastic xenoliths are interpreted as constituents of the outer zone of a cooling diapir, whereas the high temperature xenoliths come from the center.

G6

COOLING RATE ESTIMATES FROM MINERAL ZONATION : RESOLVING POWER AND APPLICATIONS

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Mineral zonation observed in peridotite phases may be useful for estimating cooling rates and for inferring the tectonic histories of the sampled mantle. The basic cooling rate estimation method is to compute numerical solutions of the diffusion equation for assumed initial conditions and a range of cooling rates, and to match these curves to observed profiles. We have undertaken a modelling study to test the resolution of this method under linear and radial geometrical configurations. The geometries have been assumed to be ideal, but we have determined the effects of uncertainty in parameters such as diffusivities and initial temperature upon our cooling rate estimates. These experiments reveal the limits of the method, but also suggest the possibility of estimating parameters like the diffusivities when other variables can be estimated in some other way. The method has been applied to discrete garnets with peridotite inclusions from Colorado Plateau ultramafic diatremes. All phases are assumed initially to have been homogeneous. Geothermometry indicates they cooled to near or below 700º C before diatreme eruption. Though olivine inclusions are homogeneous, surrounding garnets are radially zoned in Fe-Mg for 50-100 micrometers. Enstatite crystals are zoned in Fe, Mg, Ca, and Al to at least 200 micrometers from enclosing garnet. We have tested the range of cooling rates, initial temperatures, diffusivities and enthalpies in the olivine-in-garnet and enstatite-in-garnet systems which are consistent with the profiles obtained by electron microprobe observations.

G7
ZONED PYROXENES IN ULTRAMAFIC ROCKS

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The pyroxenes from some lherzolites in alpine type ultramafic intrusions are compositionally zoned. The zonation is more pronounced in cpx than in opx. The cores of pyroxene porphyroblasts are richer in Al than the rims. A similar trend is observed for Na in clinopyroxenes. In some cases zonation of pyroxenes is also found in ultramafic nodules from alkali basalts. Sometimes reversed zoning occurs. Neoblasts commonly have the same composition as the rims of the porphyroblasts.

In order to study the behaviour of trace elements we have separated by handpicking porphyroblastic clinopyroxenes from a lherzolite from Lherz. The surfaces of these pyroxenes where painted with ink and then ground to less than 200 microns. With this method rims and cores of the pyroxenes could be distinguished and separated. The two separates were analysed by INAA. A lower Na content of the rim fraction may indicate loss of jadeite component. This would also explain the parallel depletion of Cr and possibly the heavy REE in that fraction (1). Because of slight differences in REE contents between the two fraction we expect differences in Sr- and Nd-isotopes. These measurements are in progress. The results will give us a tool to estimate the time of uplift of ultramafic complexes.

Lit. E. Jagoutz et al. In: The Mantle Sample: Inclusions in Kimberlites and Other Volcanics (F.R. Boyd and H.O.A. Meyer, eds.), p. 382. Amer. Geophys. Union, Washington, D.C.

G8
CHEMICAL DISEQUILIBRIUM IN SPINEL-LHERZOLITES FROM ARIEGE (FRENCH PYRENEES).

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Detailed microprobe analyses have been performed in 45 spinel-peridotite samples from the Lherz and Freychinede ultramafic bodies representative of the exceptionally-wide modal and chemical variation found in these bodies.

Regardless of this between-sample variation, in each individual sample, whereas olivine composition is invariable, spinels and pyroxenes, especially orthopyroxenes, show irregular and sometimes wide chemical variations from nearly a constant composition in the core of the porphyroclasts to their margins and to the coexisting neoblasts. In pyroxenes, Al and, to a lesser extent, Cr and Na contents decrease. Spinels display the strongest variations, due to the combination of $FeAl_2O_4$ enrichment with a later $FeCr_2O_4$ increase.

By applying various geothermometers, two groups of temperatures have been estimated at 900°-950°C and 700°-750°C respectively. The first represents the final equilibrium state reached during the main stage of deformations and recrystallizations which occurred in the uppermost mantle (13-15 Kb) in all Pyrenean lherzolitic bodies. The second is believed to represent a partial heterogeneous reequilibration which occurred during the subsequent ascent of these ultramafic slices and their emplacement in the lower crust before their solid extrusion in Cretaceous limestones.

The present disequilibrium observed in these ultramafic complexes strongly contrasts with the chemical homogeneity which seems to exist in most spinel-peridotite xenoliths whatever their textures and equilibrium temperatures (900° to 1200°C).

G9
THE ULTRAMAFIC-GRANULITIC ASSOCIATIONS: AN INDICATION OF PALEO-MOHO DISCONTINUITIES.

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The very high pressure parageneses of mafic-ultramafic associations and the common field relationships of these rocks with crustal granulite-facies rocks suggest a two stages emplacement model for such peridotitic bodies.

A- The first stage could be related to convective processes involving "diapiric" uprise and moderate partial melting of a fragment of the mantle. The mafic-ultramafic associations re-equilibrated at depth near the subcontinental Moho P.T. conditions.

B- The second stage involves the emplacement to their present environment of the ultramafic bodies together with the deep seated continental crustal rocks as a result of two different processes:

1- Emplacement along passive margins during extensional tectonic regime; creation of oceanic crust involves a preliminary crustal thinning and occurence of the mantle at shallow depth on each bank of the oceanic area. This situation is observed along the Galicia Bank.

2- The emplacement as a result of a compressive stage after crustal thinning may lead to two different situations:

a) The previous structural relationships between ultramafic (mantle) and granulitic (crustal) rocks are more or less preserved, as shown in the Ivrea Zone and in the Beni-Bousera and Ronda area; these concordant units are overthrust upon more superficial units pointing out mega-dislocations involving the whole upper mantle/lower crust pile.

b) The previous upper mantle/lower crust structural relationships were disrupted: ultramafic and granulitic rocks occur as scattered bodies along deep crustal transcurrent lineaments. This situation has been recognized in the northern Pyrenees and along the Southern border of the Rifo-Kabylean Belt.

G10
KIMBERLITES IN THE EASTERN UNITED STATES: LOCATION AND DEPTHS OF ORIGIN RELATED TO MID-ATLANTIC TECTONISM.

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Early Mesozoic, diatreme- and hypabyssal-facies kimberlites in the Valley and Ridge and the Appalachian Plateau Provinces of the Eastern USA record mantle perturbations associated with the early phases of Mid-Atlantic rifting.

The depth of generation of the kimberlite melts seems to correlate with the distance from the rift location. Within the Valley and Ridge Province (Tennessee and Virginia), the kimberlites are highly

altered and represent diatreme-facies with considerable volatile autometasomatism. To the west in the Appalachian Plateau (E. Kentucky and S.W. Pennsylvania), fresh rock contains abundant peridotite xenoliths. Garnet lherzolites yield pressures equivalent to depths of 150 km and 160-170 km, respectively. Megacryst chemistry records near-isobaric fractionation over ~200°C (1350-1150°C). This is like the steep, inflected limbs of the Lesotho-type geotherms. Further into the Plateau, in New York State, megacrysts record a 100 km depth and 1100-1050°C. Spinel megacrysts and spinel peridotite xenoliths also represent a shallower origin. Eclogite xenoliths in the New York and Tennessee kimberlites indicate this to be a widespread component of the lower crust in the E. USA.

The occurrences in New York lie along a N-S joint pattern, that in S.W. Pennsylvania runs for 4-5 km along a NW-SE fault, transform to the prevailing structure (perhaps in a manner analogous to similar occurrences related to South-Atlantic rifting, e.g., Marsh, 1973). The ages of the southern occurrences are older than those in the North, reflecting progressive northerly rifting with time. All of the features discussed above can be explained by the prevailing tectonic regime for the Eastern United States during Early - Mid Mesozoic times.

G11

TEMPORAL AND SPATIAL PATTERNS OF ALKALI CONTINENTAL VOLCANISM: A TEST OF THE HOTSPOT CONCEPT

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The origin of kimberlite magma is investigated by compiling the known ages and locations of kimberlites, carbonatites, and other alkali continental intrusions. Because different proposed theories of origin make somewhat different predictions concerning eruption timing and location, these data help constrain speculation. The simplest model to test is the hotspot theory which predicts that the data must be self-consistent with plate motion over a set of mutually fixed magma sources. Other testable models include the reactivated fracture hypothesis which predicts linear patterns with uniform ages and the asthenospheric shear model which predicts craton-wide volcanism at times of rapid plate movement.

The post-Paleozoic igneous record of the Atlantic-bordering continents is found to be most consistent with the fixed hotspot concept. The same absolute plate motions which explain the majority of known seamount ages on the Atlantic ocean floor by fixed hotspots also explain most of the continental intrusions, including kimberlites. The reactivated fracture hypothesis is less satisfactory because many of the volcanic lineaments have demonstrable age progressions along their length. The shear melting model seems inconsistent with the great variety of ages observed within single cratons, although the data do suggest a relative peak of volcanic activity during the Cretaceous interval of rapid seafloor spreading.

G12

MINERALOGY AND COMPOSITION OF ABYSSAL AND ALPINE-TYPE PERIDOTITES

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Abyssal and alpine-type peridotites share the mineralogic and compositional features of the depleted residues of mantle melting and magma generation. Within the somewhat limited compositional spectrum of mantle peridotites, however, there are systematic differences between these different peridotite types which reflect melting in very different physical environments. Abyssal peridotite localities are characterized by very restricted mineral compositions and a relatively high abundance of modal diopside. It is apparent that melting of abyssal peridotites in general does not procede beyond the 4-phase field Ol-En-Di-Sp, and accordingly melt compositions are constrained by the four phase pseudo invarient point.

In contrast, alpine-type peridotites are frequently highly depleted compared to abyssal peridotites, and many have lower Di/En ratios. Frequently they have highly Mg, Al-poor, and Cr-rich mineral compositions lying entirely outside the range for abyssal peridotites. In addition, many alpine-type peridotites show very large local variations in degree of melting, often with large ranges of mineral compositions. It is evident that most alpine-type peridotites have melted well into the three phase field Ol-En-Sp under very different conditions than melting of abyssal peridotites.

These differences between abyssal and some alpine peridotites we attribute to hydrous remelting of abyssal peridotites in arc environments and their eventual emplacement there as ophiolite complexes. Thus many ophiolite complexes contain mantle peridotites ranging in composition from the abyssal mantle to the highly depleted residues of the generation of arc-magmas; possibly reflecting local variations in the availability of water during the last stages of melting.

G13

MAGMATIC AND TECTONIC EVENTS IN AN OCEANIC DIAPIR.

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The lherzolitic massif from Monte Maggiore, Northern Corsica, France (3x1.5 km) which belongs to an ophiolitic complex rests tectonically on a pile of thrust slabs. Structural, petrological and mineralogical studies have been engaged to determine the chronology of coupled magmatic and tectonic events during diapiric uprise of an oceanic mantle.

The oldest relict mantle, consists of layered and folded Cpx-rich peridotites evolving from Sp-free rocks to Sp-bearing ones. They have suffered limited or extensive partial fusion events, respectively initiated by pervasive injections of limited amounts of alkali-basaltic liquids or larger volumes of Ol-rich tholeiitic magma.

Circulation of alkali-rich liquids favoring the propagation of cracks have led to local enrichment of Al, Ti, Na, K, P and Zr as testified by the composition of the phases and the thermal disequilibrium. A mappable layered Pl-rich peridotite, towards the center of an ovoid lens of depleted peridotites (0.8-0.5 km) indicate fractionation of Ol-Sp-Opx-Cpx and Pl during magma ascent.

During progressive uprise of the mantle, Opx disappears as a liquidus phase in the least evolved

cumulates. Dykes with straight boundaries are fil-
led by plastically deformed gabbros. The rotation
of Cpx lineation has recorded the displacement of
peridotite blocks during magma injection.

A more superficial magmatic event is indicated
by fresh basaltic dykes of M.O.R.B. composition.

G14

GABBRO DIKES IN COMPOSITE XENOLITHS FROM HUALALAI

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Two composite xenoliths found in the 1801
Kaupulehu alkali olivine basalt flow of Hualalai
volcano, Hawaii provide evidence for crystal-
liquid separation processes in basaltic magmas
ascending through narrow dikes at relatively
shallow depths.

Specimen 1 shows a single, sharp, planar con-
tact between dunite and gabbro. The gabbro has an
allotriomorphic-granular texture and consists of
about 50% each of aluminous calcic clinopyroxene
(6.0 wt.% Al_2O_3) and plagioclase (An_{61}) with a
few percent of angular grains of olivine (Fo_{78}).
All of these minerals, as well as the olivine
(Fo_{87}) of the dunite, contain bubbles of CO_2.

Specimen 2 consists of a straight, parallel-
sided olivine-bearing gabbro dike (1.5 cm wide)
cutting clinopyroxenite wallrock. No composition-
al gradients are apparent in either lithology.
CO_2 bubbles are present in all phases. The dike
has an irregular distribution of clinopyroxene
(7.5 wt.% Al_2O_3) and plagioclase (An_{65}), and
contains polycrystalline aggregates of olivine
(Fo_{79}), interpreted as clasts of subjacent dunite
wallrock which were carried in and reacted with
the dike magma before crystallization of clino-
pyroxene and plagioclase.

The simple mineralogy of the dike rocks is
consistent with formation by crystal accumulation
(from flowing magma). Pressures cannot be specif-
ied well, but are possibly 5 to 10 kb. The
absence of typical Cr-diopside, spinel lherzolite
xenoliths at Hualalai (in contrast to their rel-
tive abundance on Oahu) may imply a relatively
shallow origin for the entire Hualalai suite. It
is possible that the widely-studied dunites,
although now possessing porphyroclastic textures,
were originally formed also by crystal accumul-
ation (from either tholeiitic or alkali basalt
magmas) and are not samples of residual mantle
beneath Hawaii.

G15

QUENCHED PYROXENITE XENOLITHS FROM THE MZONGWANA KIMBERLITE DIKE, TRANSKEI, SOUTHERN AFRICA

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Part of a large suite of garnet pyroxenite
xenoliths in the Mzongwana kimberlite dike have
quench textures. Others have polygonal granoblas-
tic or transitional textures. Bronzite, rutile,
and ilmenite form acicular crystals in sprays in
the quenched rocks; diopside has crystallized as
chains of fine granules. In rocks with transi-
tional textures, bronzite crystals form thin,
radiating blades up to 0.5-1 cm. In granoblas-
tic pyroxenites the bronzite and diopside have

crystallized as strain-free polygons 0.2-0.5 mm
in diameter and garnet grains are sieved with
fine inclusions.

About a third of the Mzongwana pyroxenites
contain segregations of garnets that appear to
have developed during nucleation and crystalli-
zation. Amphibole (potassic kaersutite) has
crystallized along the borders of garnet segre-
gations in two pyroxenites, where it is associ-
ated with Ti-rich phlogopite and with pool-like
zones of serpentine and calcite. The amphibole
is anhedral in contact with garnet but has well
developed crystal faces in contact with the
serpentine and calcite pools.

The presence of primary garnet and amphibole
suggests that these pyroxenites formed at a
depth of about 100 km, substantially shallower
than the depth of 150 km at which the kimber-
lite eruption is believed to have originated.
Quench textures would be quickly eliminated by
recrystallization at such depth and hence must
have formed in some process that was essentially
coincident with eruption. It is suggested that
the Mzongwana kimberlite entrapped pyroxenite
magma during eruption and that the liquid
pyroxenite became quenched in contact with
erupting kimberlite.

G16

THE ORIGIN OF GLASS IN ULTRAMAFIC XENO-LITHS

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Glass is a ubiquitous minor phase in high pres-
sure xenoliths in alkalic basalts. We selected 3
samples for detailed microprobe investigation. A
dunite from Hualalai contains glasses of both
andesitic (anal. A) and anorthositic (anal. D)
composition. The former typically coexists with
chromite, sulfide and CO_2-rich fluid as inclus-
ions (up to 50 μm) in olivine. The 4% sum defici-
ency is interpreted as H_2O. The anorthositic
glass occurs as sinuous veinlets (up to 30 μm
wide) within or cross-cutting olivine and chrom-
ite. A Canary Is. spinel lherzolite also contains
andesitic glass in veinlets (anals. B,C); minor
quench Ca-poor pyroxene is present. These glasses
are also apparently hydrous, and have higher Ca,
Mg and total Fe but lower K, Ti and P than the
andesitic glass from Hualalai. In a spinel lherz-
olite from Mt. Leura, Victoria vesicular glass
(anal. E) occurs with phlogopite in a vein.

We believe that the andesitic glasses found in
these and other spinel lherzolites are produced
largely by decompression during ascent as incong-
ruent "flash" melts of low melting minerals. The
anorthositic glass in the dunite may represent
original intercumulus plagioclase. The andesitic
glass in this sample may have originated as trap-
ped melt+vapor±chromite±sulfide inclusions simil-
ar to those observed in submarine basalts; the
present glass composition may result from subseq-
uent crystallization of olivine and possible
admixture with solute originally dissolved in the
high pressure fluid phase.

Representative glass compositions

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SUM
A.	63.1	0.96	20.4	2.3	0.0	0.8	4.2	1.3	2.5	0.23	95.79
B.	61.4	0.02	18.8	3.3	0.0	2.7	8.0	1.0	0.39	0.0	95.61
C.	57.7	0.02	18.2	4.1	0.0	4.1	11.3	2.4	0.45	0.0	98.27
D.	51.6	0.16	29.5	1.0	0.0	0.40	13.6	3.7	0.23	0.0	100.19
E.	59.1	3.5	18.4	3.0	0.0	2.1	4.5	2.2	5.6	0.45	98.85

G17

PODIFORM CHROMITE ORE BODIES : A MODEL OF MAGMA FLOW THROUGH DIKES AND CAVITIES

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Podiform chromites ores are found in ophiolite complexes which are supposed to be formed under oceanic ridge. The ore cristallises and accumulates from silicate magma flowing through dykes. Field data support the fact that the accumulation of chromium was set in cavities 5m thick and hundred meters high somewhat larger than the usual thickness of dykes (0.10 – 1m large). The thermal contrast between the magma and the peridotite walls generates in these cavities a strong convective circulation.

Numerical models of the flow accross the feeding dyke and cavity are presented. The needed physical conditions necessary for the formation of the ore are presented. They put constrains on the thickness, flow intensity, spatial and temporal activity of these dykes. They are compared with these drawed from other geophysical and geological studies, and give thus some light on the possible processes acting under the magma chambers in oceanic ridge environment.

G18

HIGH TEMPERATURE DIKES IN MANTLE PERIDOTITES : ORIGIN BY HYDRAULIC FRACTURING DURING PLASTIC FLOW

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The orientation of high temperature dikes has been studied with respect to the plastic flow foliation and lineation in peridotites from several massifs and from basalt xenoliths. Layering and dikes are composed of various types of pyroxenites and gabbros ; dunites, thought to represent residuae along high temperature dikes, have been also studied. Layering is composed of dunites, websterites and/or orthopyroxenites, usually with the same minerals as in the host peridotite. The same rock types can be observed in the dikes emplaced early during plastic deformation but the sequence tends to evolve towards more ariegitic or gabbroic facies.

Dikes emplaced during plastic flow display two dominant preferred orientations, one is at high angle to the stretching lineation, the other is parallel to the shear planes deduced from the flow regime analysis in the peridotite (a unique shear plane oblique to the foliation in the case of rotational flow, two shear planes conjugate with respect to the foliation in the case of ir-rotational flow). Fracturing in all these orientations is ascribed to the magma pressure created by partial melting. Comparatively low magma pressure and high applied deviatoric stress result in shear fractures ; high magma pressure and moderate applied stress result in tension fractures (at high angles to the lineation). Dikes emplaced before or early during plastic flow are strongly deformed and tectonically rotated towards the foliation and lineation directions. For a large deformation they become parallel to the foliation orientation. The ubiquitous layering of mantle peridotites can originate in this way.

H

Kimberlite
Research Notes

H1

KIMBERLITES IN CHINA AND THEIR MAJOR COMPONENTS: A DISCUSSION ON THE PHYSICOCHEMICAL PROPERTIES OF THE UPPER MANTLE

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Kimberlite bodies have been found mainly on the North China Platform, such as near the Huangjiachuan, Majuan and Tumen villages, and some on the Yangtze Platform, such as near the Shenchong and Pengjiabang villages.

The Huangjiachuan and Majuan kimberlite bodies occur on the western and eastern sides of the Tancheng-Lujiang Deep Fault Belt. The Huangjiachuan kimberlite bodies appear in a NNE trending zone, and form two groups of kimberlite pipes and veins and one group of kimberlite veins, intruded into the Archaean hornblende-biotite gneisses, Proterozoic migmatites and Cambrian limestones, thin layered sandstones and shales. The Majuan kimberlite bodies lie in a nearly east-west trending zone and form three groups of kimberlite pipes and veins intruded into the Sinian quartzites, thin layered argill(ac)eous limestones and shales and Cambrian limestones.

The Tumen groups of kimberlite veins are located in a NNE trending zone on the western side of the Taihangshan Deep Fault Belt, and intruded into Cambrian limestones.

The Shenchong group of kimberlite veins is located in a NE-ENE trending zone on the southern side of the Taihangshan Deep Fault Belt and intruded into Cambro-Ordovician limestones and dolomites.

The Pengjiabang group of kimberlite pipes and veins occur in a NW trending zone and intruded into Cambrian limestones. They are closely related to the NW trending deep faults on the northern border of the Yangtze Platform.

Most of the veins are composed of porphyritic kimberlite. The rims of some veins are formed of kimberlite-breccia with porphyritic kimberlite at their centres. Individual veins are thinned out, and there is a transition from porphyritic kimberlite to kimberlite-carbonatites. Some veins show a linear flow structure.

Most of pipe's cores are porphyritic kimberlite and their rims are usually kimberlite-breccia. In some kimberlite pipes has been found kimberlite-carbonatite. Some groups of kimberlite pipes at depth are transformed into veins, and individual pipes are thinned out. In an open mining pit of a kimberlite

pipe near the Huangjiachuan village, the porphyritic kimberlite shows linear flow structure having NW 55° trend and dip to north at an angle of 40° at the contact with kimberlite-breccia. In the Majuan and Huangjiachuan area, some blind kimberlitic pipes were found at shallow depth. This fact indicates that they are of hypabyssal origin.

The kimberlites are strongly serpentinized and carbonatized, and sometimes silicified. Fresh kimberlitic rocks only locally appear at great depth in a pipe of the Huangjiachuan area. The major minerals of the kimberlites are olivine (serpentinized), phlogopite, pyrope, chrom diopsite, clino-pyroxene, picotite, magnesiochromite, perovskite, ilmenite, magnetite, rutile, anatase, apatite, moissanite, zircon, caldasite, serpentine, calcite, graphite, and diamond, and very rare picrotanite. The pyrope is usually altered and covered by a green or black "shell".

The kimberlites are one kind of sub-alkaline magmatic rocks. They have very high volatile component. Chemical composition of porphyritic kimberlite is as follows: SiO_2 25.84-40.15%, Al_2O_3 1.47-3.5%, MgO 21.63-35.1%, MnO 0.1-0.23%, P_2O_5 0.26-2.94%, K_2O (0.17-3.9%) more than Na_2O (0.04-1.32%), in some samples K_2O(0.05-0.27%) less than Na_2O (0.07-1.65%); CO_2 0.03-23.1%, H_2O 1.50-12.72%, and Cr, Ni and Co less than that in ultrabasic rocks.

The kimberlites show no significant variation in different tectonic settings. This indicates that the chemical properties of mantle sources were also not much different.

But the kimberlites from different tectonic zones and different orogenic belts vary in their ultramafic xenolithes and mineral components, It indicates difference in physicochemical properties of the upper mantle. For example, the Huangjiachuan kimberlite bodies are the product of the Yenshanian orogeny. They contain peridotite and chrome-spinel lherzolite xenolithes. In thin-sections of rocks from Huangjiachuan bodies, the fresh clino-pyroxene crystals show exsolution texture with platy intergrowths of ilmenite. This ilmenite might come from more 250 km depth in the upper mantle because pyroxene and ilmenite can form a solid-solution at the pressures greater than

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70 kbar. The Majuan kimberlites of the Caledonian age contain xenolithes of peridotite, garnet-mica pyroxenite and the early large crystals of phlogopite. In thin sections of rocks from Majuan bodies, the fresh acicular clino-pyroxene crystals and the fresh platy phlogopite crystals show their microspinifex texture respectively, and the early large crystals of phlogopite show exsolution texture with platy intergrowths of magnetite. These facts indicate that the pressures and temperatures were unstable in the upper mantle.

Under the electron microscope, the (111) crystal faces of magnesiochromite show a growth texture from polycrystalline seeds which indicates that magnesiochromite might be formed at high pressures in the mantle. The (111) crystal faces of the rhombic-dodecahedron-octahedron shaped diamond shown the dislocation growth lamellae, which lie at an angle of 35° with the stress plane, and the arcuate impact texture has been found on the (111) crystal faces of diamond octahedra. This dislocation of growth lamellae on the crystal face

(110) of diamond shows that some diamond crystals have grown in the solid or sub-solid stage, but not in the liquid or gas state. The arcuate impact texture on the (111) crystal face of diamond octahedra appears as a result of the impact stress after crystal growth.

The Tumen kimberlites are the product of the Himalayan movement. In these kimberlites, some altered pyroxene exhibits chrom spinel exsolution textures. It is suggested that the depth of the original kimberlitic magma in this area was probably less than that of Huangjiachuan kimberlitic magma.

The Shenchong and Penjiabang kimberlites were formed during the Caledonian period. In the Shenchong kimberlites, the picrotanite is rare, too; but anatase and rutile contain more niobium. The lherzolite xenolithes found in the Penjiabang kimberlites indicate that the depth of magma chambers for the Shenchong and Penjiabang kimberlites might be less than 250 km.

H2   GEOLOGY OF BRAZILIAN KIMBERLITES

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In the Late Cretaceous, the South American Platform was affected by a huge magmatism accompanied by the intrusion of a great amount of kimberlites, rocks with kimberlite affinities, alkaline rocks and associated carbonatites (Svisero et al. 1979a). The majority of the bodies with kimberlite characteristics are located in the west part of Minas Gerais State ; nevertheless, there are several occurences in the States of Mato Grosso, Piaui, Santa Catarina and Rondônia.

Svisero et al. (1979b) summarized the main geological surveys of kimberlites carried out in Brazil in the last decade by local and foreign mining companies. Although much of these results have not been published yet, it is admitted that the number of diatremes and rocks with kimberlite affinities surpasses two hundred bodies. Some of these intrusions have been proved to be kimberlites, namely the Vargem 1 and the Redondão (Svisero et al 1977), as well as the diatreme of Limeira 1, Limeira 2 and Indaiâ (Svisero et al. 1980). Others are still being investigated.

In an attempt to increase the information regarding Brazilian kimberlites, this paper presents mineralogical and geological data on Limeira 1, Limeira 2, Indaiâ 1, Indaiâ 2, Vargem 2, Santa Clara, Japecanga, Pimenta Bueno, Mamões, Poço Verde and Morungaba kimberlites. Excepting Pimenta Bueno in Rondônia, all the other mentioned kimberlites are located in west Minas Gerais which seems to be the most important kimberlitic province in Brazil.

Kimberlites occur in west Minas Gerais as diatremes which range from 50 to 400 meters in diameter or as small dikes, mostly clustered in the headwaters of the Paranaiba River. Although weathered on the surface, the yellow-ground usually contains several kimberlitic minerals such as Cr-pyrope garnet, Mg-ilmenite and diopside, whose chemical compositions are similar to their counterpart kimberlites from worldwide localities. Twelve diatremes have been proved to be true kimberlites up to now ; geological and geophysical data, however, suggest that the total amount may reach for beyond that number.

Limeira 1 is a dark porphyritic kimberlite with large amounts of olivine, monticellite, phlogopite, perovskite and opaque minerals, dispersed in a fine-grained

matrix having the same mineral assemblage plus serpentine and carbonates. Geophysical surveys (scintilometry, electro-resistivity, magnetometry and thermometry) showed a regular almost oval outline measuring 300 x 250 meters. Limeira 2, the twin body of Limeira 1, is a small elliptic diatreme whose N-S main axis is no longer than 80 meters. Limeira 2 has a gray aphanitic matrix rich in phenocrysts of fractured olivines and numerous xenoliths of crustal rocks, breccias and dunite. Indaiâ 1 is similar in size, color, texture and mineralogy to Limeira 1. Indaiâ 2 is a small satellite of Indaiâ 1, similar to Limeira 2. Limeira's and Indaiâ's diatremes, 1.5 Km apart, are all intrusive in rocks of the crystalline basement, mostly granites, schists and cataclasites. Vargem 2, Santa Clara, Japecanga, Mamões, Poço Verde and Morungaba kimberlites have been characterized by mineral chemistry of their resistant minerals recovered from yellow-ground .

As mentioned before, kimberlites occur scattered throughout Brazil such as Pimenta Bueno in Rondônia and Redondão in Piaui. Despite the lack of specific studies, the kimberlites of Paranatinga, Mato Grosso State, and the recent discoveries of Lajes, Santa Catarina State, should be mentioned as well. Geologic and tectonic characteristics of these occurences suggest the existence of at least four more kimberlitic provinces in Brazil besides that of west Minas Gerais : Pimenta Bueno in Rondônia, Gilbuès in Piaui, Lajes in Santa Catarina and Paranatinga in Mato Grosso.

West Minas Gerais, Lajes and Paranatinga Provinces display geological similarities, as all are located on the border of the Paleozoic Parana Basin ; furthermore, they are related to Cretaceous tectonic arcs that favoured the intrusion of a great number of alkaline rocks and associated carbonatites. Gilbuès Province in the southern Paranaiba basin, another Paleozoic basin in north Brazil, apparently is related to reactivation of important Precambrian structures. Field relations of Redondão, the only reported kimberlite in this province, indicate the kimberlite as Cretaceous. On the other hand, very little is known about the tectonic evolution if Pimenta Bueno in east Rondônia. The kimberlites could either be related to Proterozoic tectonics or be Cretaceous as in West Minas Gerais, Gilbuès, Lajes and Paranatinga Provinces.

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H3 RICHTERITE-ARFVEDSONITE-RIEBECKITE-ACTINOLITE ASSEMBLAGE FROM MARID DIKES ASSOCIATED WITH ULTRAPOTASSIC MAGMATIC ACTIVITY IN CENTRAL WEST GREENLAND

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Introduction

Dawson & Smith (1977) proposed that a mica-amphibole-rutile-ilmenite-diopside (MARID) suite of xenoliths in kimberlites were cumulates from a highly oxidized kimberlitic magma in the upper part of the mantle (above 100 km). This letter reports lamproite dikes with MARID-type mineralogy from central West Greenland believed to have been emplaced as a magma and crystallized in the upper crust at a depth of less than 10 km. Systematic Ti-zoning trend in the alkali amphiboles points to a low valence of titanium and consequently reducing crystallization conditions.

Regional setting

Alkalic plutonic activity in the Sisimiut (Holsteinborg) area of central West Greenland is well known (Scott 1979, 1981; Larsen 1980), including ultrapotassic micaceous lamproites (1227 m.y.) and micaceous kimberlitic dikes (587-500 m.y.). The regional distribution of the rocks from these two intrusive events is still poorly understood. However, kimberlitic dikes seem to be related to the Sarfartôq carbonatite complex (Larsen 1980) and to an area around Sisimiut (Scott 1981). Ultrapotassic lamproites are more widespread and may be related to a regional intrusive event, although the main reported occurrences are related to the Ikertôq and Ndr. Strømfjord shear zones (e.g. Scott 1981) within the Nagssugtoqidian mobile belt (Bak et al. 1975). A third type of ultrapotassic dikes containing high amounts of alkali amphiboles are reported here. Their regional distribution and age relation to the micaceous lamproites and kimberlites are unknown. The few recorded dikes are distributed over the same area as the kimberlites (e.g. Larsen 1980, p. 67).

Petrography of the amphibole lamproites

Large euhedral clinopyroxene macrocrysts occur showing partial resorption and neocrystallization to actinolite. Alkali amphiboles, phlogopite and K-feldspar are ubiquitous groundmass phases together with ilmenite, rutile, actinolite, apatite, quartz and carbonate. Subhedral to euhedral groundmass micro-phenocrysts of K-feldspar are often replaced by a fine-grained turbid mixture of secondary minerals. Alkali amphiboles are dominated by brown to yellow-green richterite which may be interstitially zoned toward either nearly opaque arfvedsonite or green-bluish magnesio-arfvedsonite. A blue fibrous riebeck-itic mineral occurs as a late crystallizing phase overgrowing zoned richterite. Rutile occurs as a discrete anhedral groundmass phase and as rims on sub-hedral to euhedral groundmass ilmenite.

Crystal chemistry of the alkali amphiboles

The amphibole chemistry is calculated according to the general formula $A_{0-1}B_2C_5^{VI}T_8^{IV}O_{22}(OH)_2$. Estimation of Fe^{3+} shows the main part of the amphiboles to contain excess cations for charge balance. In assigning cations to structural positions Ti is therefore assumed to fill the tetrahedral position. This scheme is consistent with chemical analyses of natural rich-terites (e.g. Prider 1939).

The dominant alkali amphibole is a potassium-titanian-richterite with the simplified formula (Table 1) $K_{0.7}NaCa(Mg,Fe)_5(Si,Ti)_8O_{22}(OH)_2$. Only limited Al substitution is observed, whereas Ti occupancy of tetrahedral sites is high. The B sites are occupied by equal amounts of Ca and Na, and the A sites are nearly filled ($Na_A + K_A = 0.9$). The highest Mg/(Mg+Fe) ratio obtained is 0.8. Two important zoning trends have been detected and texturally related to a volumetrically minor interstitial crystallization.
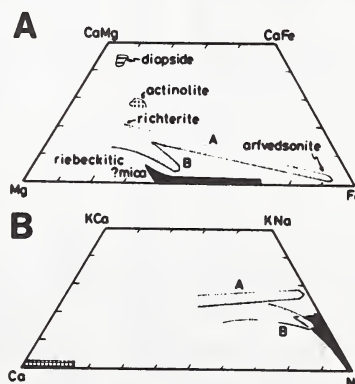

Figure 1. Ca-Mg-Fe (A) and K-Ca-Na (B) trends for alkali amphiboles from amphibole lamproites, central West Greenland. Two zoning trends are identified in the groundmass (A and B).

Zoning A (Fig. 1): Complete solid solution occurs between the richterite and the potassium-titanian-arfvedsonite (Table 1). The tetrahedral sites are nearly filled by Si while Ti occurs mostly as an octa-hedral coordinated cation in the Fe-rich amphiboles.

Within the zoned region, Mg/(Mg+Fe) ranges from 0.8 to zero. Ti increases from 0.5 to 0.8 formula units, whereas Al decreases from 0.2 to below the detection limit. Ca varies from 1 to 0 and shows a positive correlation with Na (1 to 2), while K remains constant or increases slightly (Fig. 1).

Zoning B (Fig. 1): A solid solution between rich-terite and a potassium-titanian magnesio-arfvedsonite also occurs (Table 1). The Mg/(Mg+Fe) ratio extends to only 0.60 and hence contrasts significantly from the Fe-enrichment of the arfvedsonites of trend A (Fig. 1). Tetrahedral sites are almost fully occupied by Si and Ti occurs only as octahedrally coordinated cations. Ti varies from 0.5 to 0.3 with decreasing Mg/(Mg+Fe). The Ca $\rightleftharpoons$ Na substitution is identical to that of trend A. The main difference between the two trends is the degree of iron and titanium enrichments.

Some analyses show a significant decrease in K and, overgrowing the magnesio-arfvedsonite often occurs a fibrous riebeckitic mineral (Table 1). Calculated as a amphibole the mineral contains excess silica (Si=8.2-8.5). The analyses are best calculated as a mica with the general formula $Na_2(Fe,Mg)_5Si_8O_{20}(OH)_4$ but, however, with a rather unusual composition for a mica.

Cation substitution: Estimation of Fe^{3+} from charge balance shows the Ti and Fe-rich amphiboles to contain excess cations. It is possible that excess Ti was incorporated in the structure at high temperature and then exsolved during cooling, now seen as a very fine pigmentation of the grain margins. When this 'excess' Ti is extracted from the calculations Fe^{3+} can still not be satisfactorily calculated. Another possibility is that Ti occurs with a lower valence than assumed or alternatively the amphibole contains excess oxygen. The latter possibility is, however, considered unlikely as no indication of a highly oxidized environment is seen from the other oxide and silicate groundmass phases. Calculating all Fe as Fe^{2+} and charge balance the formula with Ti^{3+}:

Ti^{4+} give results indicating most titanian as Ti^{3+}, and a positive correlation between Ti^{4+} and total Ti. It is therefore considered most likely that the strong Ti-Fe trend in the alkali amphiboles record a reducing melt. In the Mg-rich amphiboles, however, minor Fe^{3+} contents can be calculated, with all titanium as tetravalent, and increasing with total Fe. This indicates that the cation substitutions differ in the two observed zoning trends and can be related to variable redox conditions.

The main substitution observed in the Fe-enrichment trend (A) is a Ca $\rightleftharpoons$ Na exchange in the B sides coupled with octahedral Mg $\rightleftharpoons$ (Fe,Ti) and minor tetrahedral Al $\rightleftharpoons$ Si substitution in order to obtain charge balance. The end-members in the cation substitution can be best written as $KCa_2Mg_5Si_7AlO_{22}(OH)_2$ and $KNa_2Fe_4-TiSi_8O_{22}(OH)_2$. The latter formula is only charge balanced if Ti occur as Ti^{3+}.

For the magnesio-arfvedsonite trend (B) again a Ca $\rightleftharpoons$ Na substitution in the B sites is the dominating exchange and most likely coupled with a $Fe^{2+} \rightleftharpoons Fe^{3+}$ exchange. This gives a riebeckite end-member $Na_2Fe_3^{2+}Fe_2^{3+}Si_8O_{22}(OH)_2$. This consideration neglect minor Al $\rightleftharpoons$ Si and K $\rightleftharpoons$ Na substitution. It is interesting that the latter occur as a late crystallizing phase.

Other minerals

Groundmass actinolite occurs with a Mg/(Mg+Fe) ratio between 0.8 and 0.7 and only minor amounts of other elements (Table 1). The clinopyroxene macro-crysts are diopside ($Wo_{41}Fs_8En_{51}$). The Cr_2O_3 content ranges from 0.1 to 2 wt%. The phlogopite groundmass phase shows little variation and is comparable to other analyses from ultrapotassic rocks. However, the TiO_2 content is significantly higher (7-10 wt%) and Cr_2O_3 and Mg/(Mg+Fe) lower than in the phlogopites from MARID nodules from kimberlites (Dawson & Smith 1977). The oxide assemblage consist mainly of ilmenite with a low hematite content. The MnO content reaches 7 wt% and MgO is generally below the detection limit. These ilmenites contain the highest Mn content recorded from magmas of kimberlitic affinities (Vartiainen et al. 1978). Rutile contains also low Fe_2O_3 and generally low Cr_2O_3. Apatite is a flour-apatite and the flourine content of the mafic minerals are generally low.

Conditions of crystallization

The total pressure during solidification can be estimated as not exceeding 3 kbar (Bak et al 1975). Total vapour pressure was most likely equal to load pressure to account for abundant crystallization of hydrous minerals. Crystallization of clinopyroxene and phlogopite occurs in ultrapotassic magmas around 1100-900°C (e.g. Edgar et al 1976). Final consolidation must have occurred at very low temperature (quartz and K-feldspar).

Several lines of evidence suggest that oxygen fugacity was low in the original magma. Low Fe_2O_3/FeO in the bulk rock (0.25), low hematite in ilmenite and systematically low Ti^{4+} and Fe^{3+} calculated in the amphiboles are the main reasons. Crystallization of richterite also requires low f_{O_2} and temperature (Ernst 1968; Charles 1975). However, the high Mn in ilmenite seems to contradict this conclusion.

A tentative model can be outlined: a low f_{O_2} trend from richterite, arfvedsonite to actinolite (trend A in Fig. 1), and a high f_{O_2} trend (B in Fig. 1) from richterite, magnesio-arfvedsonite towards a riebeckitic mineral. The main difference could relate to local elevation in oxygen fugacity in the interstitial melt-fluid system.

Implication for the origin of MARID nodules

Dawson & Smith (1977) described a MARID suite of xenoliths (or glimmerites) in kimberlites. They suggested that part of these were cumulates from a highly oxidized kimberlitic magma. It is clear from the present work that their conclusion need revision. The mineralogical similarities between the present dikes

TABLE 1: Analysis and structural formula of richter-ite, arfvedsonite, actinolite and riebeckitic ?mica.

	1	2	3	4	5
SiO_2	51.84	49.45	53.09	54.59	55.05
TiO_2	4.26	6.92	2.72	0.06	1.83
Al_2O_3	1.22	0.08	0.38	0.25	0.24
Cr_2O_3	0.09	0.02	0.05	0.03	0.09
FeO	9.65	29.19	15.24	11.90	18.44
MnO	0.20	0.50	0.13	0.21	
MgO	16.05	0.67	12.44	16.83	10.78
CaO	6.32	0.16	1.88	11.86	
Na_2O	4.17	6.81	6.37	0.31	6.32
K_2O	3.64	3.35	3.08		0.39
Total	97.44	94.15	95.38	96.04	93.14
K_A	0.68	0.68	0.59		0.07
Na_A	0.17	0.14	0.16		
Na_B	1.01	1.97	1.70	0.09	1.78
Ca_B	0.99	0.03	0.30	1.85	
Fe_C	1.18	3.89	1.92	1.45	2.24
Mn_C	0.03	0.07	0.02	0.03	
Mg_C	3.49	0.16	2.80	3.65	2.34
Ti_C	0.14	0.74	0.31		0.20
Al_C			0.07		0.04
Si_T	7.56	7.89	8.00	7.95	8.01
Al_T	0.21	0.02		0.04	
Ti_T	0.33	0.09		0.01	
O	22	22	22	22	20
OH	2	2	2	2	4

1. Potassium-titanian-richterite. Core of zoned groundmass phase.
2. Potassium-titanian-arfvedsonite. Nearly opaque rim of zoned richterite.
3. Potassium-titanian-magnesio-arfvedsonite. Blue coloured rim of zoned richterite.
4. Actinolite. Groundmass phase.
5. Riebeckitic mineral calculated as a mica. Blue coloured fibrous phase overgrowing zoned richterite.

and MARID xenoliths suggest that the latter are either fragments or cumulates from, compared to a kimberlite, a very distinct non-oxidized magma type. Differences in minor elements in most minerals, as well as modal constituents, may reflect that the studied dikes represent a slightly more evolved composition than that from which MARID xenoliths are either fragments or cumulates. K-feldspar in the groundmass is the main difference between MARID nodules and the West Greenland lamproites.

L. M. Larsen reviewed the manuscript.

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H4   TRIASSIC POTASSIUM-RICH BASALTS AND COEXISTING CARBONATE MELTS IN THE ECRINS-PELVOUX AREA, FRENCH ALPS.

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Throughout the Ecrins-Pelvoux area, an explosive and effusive volcanism is essentially represented by series of sheets with a consistent stratigraphic position. Upper triassic to lower Jurassic sedimentary rocks interlayered with the volcanic sequence suggest a rifted passive continental margin. The pre-rift sedimentary sequence (argillites, black shales and dolomitic limestones) represents a upward transition from supratidal to intertidal deposits (Baron, 1981).

Numerous doleritic dikes up to several meters in thickness injected into the metamorphic basement (partly Hercynian in age) are the feeders of the overlying volcanic sequence. The mineralogical relationships and field evidence have established that the cogenetic dikes and lava flows derived from a single source. Doleritic volcanic rocks including dikes, rare sills, massive flows, tuffs and volcanic breccias are generally porphyritic, showing a change in texture from fine- to coarse-grained. The original basaltic paragenesis, based upon relict minerals (with the exception of rare fresh olivine), is alkaline in composition and have been subjected to low-grade regional metamorphism (greenschist facies; Adline, 1982).

The alkali basalts may be divided into two quite separate groups on the basis of their REE contents (fig.1) : (1) alkali basalts (Na series) show a small light-REE enrichment, lesser heavy-REE depletions and positive Eu anomalies ; (2) potassium-rich basalts (K series) – 8 to 10 % of K_2O and less than 45 % SiO_2 – uniformly have high REE contents, are strongly LREE enriched, and have a small but distinct negative Eu anomaly. However, the difference in Eu anomalies between the two basaltic sequences can be accounted for by feldspar fractionation producing a small Eu depletion in the potassium-rich basalts. Accordingly, compared to ordinary alkali basalts (Frey, 1968), the Na sequence has a low, and the K sequence a high content of REE. The potassium-rich basalts cannot be clearly related to an effect of hydrothermal alteration or greenschist metamorphism.

These rocks present a close carbonate-basalt association in space and time : carbonate occurs as pseudomorphs after plagioclase, peridot and clinopyroxene, as amygdules and smaller bleds dispersed throughout the matrix and also as veins in the rocks. Secondary carbonates fill almost all available gas bubbles and extensive fissures and appear generally in various basaltic fragments with abundant interbedded triassic sediments.

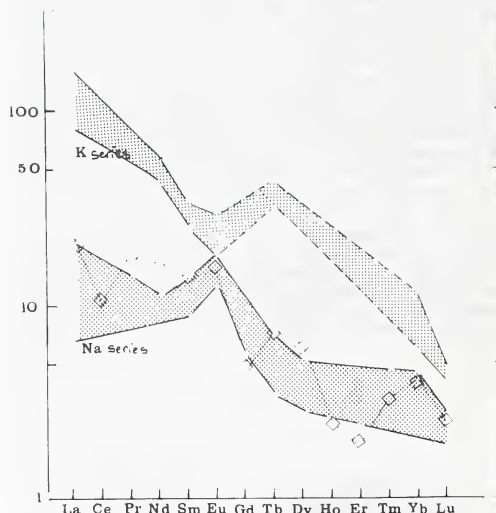Possibilities of complex interactions between

Fig. 1. Chondrite-normalized REE patterns for K series (9 potassium-rich basalts) and Na series (4 alkali basalts similar to hawaiites) ; the single line is a semi-quantitative determination.

the basaltic magma and the carbonate phase cannot be ruled out ; the origin of the carbonate may result from a mechanism of magmatic separation during cooling

Volcanic pipe and associated dikes are confined to the area of the metamorphic basement and are genetically connected with the lava flows but no contact between these rocks has been found. A North-South volcanic pipe, more than 100 m thick, is essentially filled with polygenic breccias intruded by potassium-rich lavas. To the west a dike, 1-2 m thick and 1 km-long, locally exhibits a 10 cm thick margin with small-scale brecciation of the doleritic lava and a carbonate matrix. To the east an alkaline dike, 6 m thick, shows a doleritic texture with carbonate dissemination in the matrix and peridotite xenoliths now altered through complete carbonatation.

No traces of carbonatation could be observed in the gneisses intruded by pipe and dikes and the envi-

ronmental conditions of these rocks excluded a contamination by sedimentary material. It is thus likely that these deep-seated rocks have been carbonated by a process closely related to the basaltic magma genesis.

Lava flows : occurences of secondary carbonate are typically the results of assimilation of sediments such as small dolomitic beds progressively inserted in the effusive volcanic sequence as veins and amygdaloids ; however the overwhelming majority of carbonate inclusions connected with the other types of secondary carbonates may be not attributed to this process and a magmatic origin therefore need to be considered.

Oxygen and carbon isotope variations for carbonate included in lava material. Oxygen and carbon isotope analysis have been made on carbonate extracted from 12 samples from vesicles and amygdules of lava flows (open circles) and 3 samples from 2 dikes (solid circles). In addition, 2 samples of dolomitic sediments interbedded with the basaltic lavas (solid stars) and 2 relicts of sediments included as xenoliths in lava flows (open stars) have also been analyzed, as well as the calcitic matrix of a Tl deposits (J :Jarousite, Mantienne, 1974), which cuts the triassic volcanic sequence but not the overlying sediments. Results and relationships between $\delta^{18}O$ and $\delta^{13}C$ are shown in Fig.2 for all these samples together with some classic references. Analytical measurements (R. Létolle, Laboratoire de Géologie Dynamique, Univ. Paris VI) are expressed in conventional delta notation as permil deviation from the PDB standard. For commodity, corresponding values of $\delta^{18}O$ are also expressed from the SMOW standard using the convertion scale of Pilot (1974). Taylor box : defined from extreme values from primary carbonatites estimated by Taylor et al. (1967) ; evolution trends by fractionation (F) or alteration (A) and the dispersion between calcites from matrix (M) or as phenocrysts (C) are determined by Pineau (1977) ; dashed area : values of carbonate kimberlites and associated peridotite nodules (Deines and Gold, 1973 ; Sheppard and Dawson, 1975; Pineau, 1977). Approximative limit between marine carbonate sediments (MCS) and continental carbonate deposits (CCS) ; ondulated dashed line is drawn after Rösler et al. (1968) from formations with age and environmental tectonic setting not very far from those of alpine triassic dolomites.
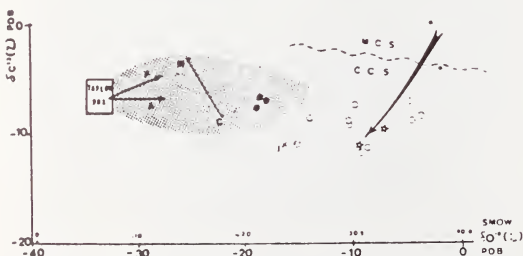

Fig.2. Oxygen and carbon isotope data for carbonates included in lava material.

First, it can be seen that the $\delta^{13}C$ values vary from -6.8 to -11.4, as do those obtained from various localities of Glarus spilites (Amstutz and Patwardhan, 1974). These values are too negative to represent a sedimentary origin, but they recall those observed in kimberlitic rocks. Nevertheless, the $\delta^{18}O$ values of the flows show an important enrichment in ^{18}O isotope , which cannot be interpreted directely in terms of igneous origin. Only the $\delta^{18}O$ values of carbonates from the dikes cutting the metamorphic basement are similar to those of kimberlites. As contamination by metasediments in unlikely in this case, and since one of those carbonate samples shows REE

patterns very similar to that of the surrounding matrix, a cogenetic origin for both silicate and carbonate can be advanced. The isotopic values obtained on both intrusive and effusive materials with $\delta^{18}O$ < 30% (SMOW), are within the range of values observed for unaltered rocks from the Mid-Atlantic Ridge, and obtained through phosphoric acid extraction (Pineau et al., 1976). The remaining samples showing low $\delta^{13}C$ and high $\delta^{18}O$ values from CO_2 liberated by the acid treatment have been interpreted by these authors as carbonates of primary origin, formed during a late-stage medium-temperature cristallization.

A sedimentary bed of dolomitic limestone has been incorporated and assimilated on a distance of a few meters by a lava flow and thus forms a very good natural experiment to in situ measure the processes of isotopic fractionation which occurs in high-temperature-lava marine-carbonate interaction. These observations show, better than any theoretical model, the isotopic behavior of C and O during destabilization and remobilization of carbonates. In lava flows, only a few millimeter to centimeter-sized varioles, usually dolomitic, may be interpreted as due to sedimentary contamination. Filled vesicles with very low $\delta^{18}C$ are likely to have a different origin, probably hydrothermal. It is generally accepted that cogenetic CO_2-rich liquid and basaltic liquid are required for the formation of kimberlites and related alkaline rocks. A similar hypothesis can be proposed for triassic carbonated lavas from the Ecrins-Pelvoux area (1) production during ascension through the sialic crust by differentiation or contamination of a special CO_2-rich magma ; (2) generation of a residual carbonate-rich liquid immiscible with normal alkali basalt magma (occels in veins or lava flows) ; (3) individualization of an independant carbonate phase which can locally dislocate and alter previously solidified lavas (carbonate breccias) ; (4) interaction of the carbonate phase with superficial non-marine water and production of hydrothermal fluids which are responsables of the final spilitic paragenesis.

On the basis of previous petrographic, mineralogical, chemical and the above isotopic evidence, this triassic alkalic volcanism would result from magmatic conditions recalling those of kimberlitic genesis. Certainly, superimposition of multiple stages of alteration together with a low grade syntectonic alpine metamorphism could a priori cast some doubts on this hypothesis ; but, whilst individual observations are not evidence these accumulation of data presented here appears as quite a strong argument for our conclusion.

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H5

THE ULTRAPOTASSIC ROCKS OF THE WEST KIMBERLEY REGION, WESTERN AUSTRALIA, AND A NEW CLASS OF DIAMONDIFEROUS KIMBERLITE

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Diamonds have recently been found in kimberlitic rocks intimately associated with the leucite lamproites (Wade and Prider, 1940; Prider, 1960) of the Fitzroy area of Western Australia (Garlick, 1979; Atkinson et al., 1982). In this paper we present a summary of the geology, mineralogy and geochemistry of the ultrapotassic rocks of the province including the diamondiferous kimberlitic rocks, here termed 'kimberlitoids' to emphasize their unusual mineralogy and geochemistry.

Geological Setting

The ultrapotassic rocks of the West Kimberley region lie immediately south of the southwestern margin of the stable Proterozoic Kimberley block, and intrude the igneous, metamorphic and sedimentary rocks of Precambrian to Mesozoic age of the Lennard Shelf and adjacent Fitzroy Trough at the northern margin of the Canning Basin as shown in the figure below. Over 100 bodies, both of leucite lamproite and kimberlitoid composition, are now known. There are three main clusters which appear to be controlled by northwesterly-trending faults at the basin margin, and major northerly-trending faults: the Lennard Shelf (Ellendale area), the Shelf Margin (Calwynyardah area), and the Fitzroy Trough (Noonkanbah area). The majority of the bodies are intruded along the axes of major northwesterly-trending anticlines, and a number are elongated in an easterly direction.

The kimberlitoids (particularly the diamondiferous bodies) are confined mainly to the Lennard Shelf and shelf margin. In the Ellendale and Calwynyardah areas they occur as clusters of pipes, rare dykes and sills; the pipes tend to form topographic lows, in some cases surrounded by upstanding rim rocks. The largest pipe has a surface area of 128 ha. Individual pipes may be simple, or complex and zoned; many have an outer zone of tuff or tuff breccia and a central magmatic core. Several bodies have associated crater sediments indicating little erosion since their emplacement.

The leucite lamproites are most abundant in the Noonkanbah area where they form topographic highs. They occur as small volcanic plugs, vents, dykes, sills and, possibly, flows. The largest body forms a zoned pluton 3 km in diameter. Many of the plugs show concentric compositional zoning and have an outer zone of breccia. Concentric and radial jointing is also common.

Age

The leucite lamproites are considered to be of early Miocene age, 17-22 m.y. (Wellman, 1973), mainly on the basis of K-Ar dating of phlogopite. Two bodies of kimberlitoid, one of which is diamond-bearing, have yielded similar ages, 20-21 m.y. by both K-Ar and Rb-Sr methods. The close spatial association of these with the other kimberlitoids and their intimate association with the leucite lamproites (e.g. clasts of leucite lamproite in kimberlitoid) suggests that the other diamondiferous Ellendale pipes are also of Miocene age.

Petrography

Both the kimberlitoids and lamproites are strongly porphyritic. The kimberlitoids contain two generations of olivine; anhedral olivine xenocrysts up to 8 mm diameter coexist with euhedral olivine microphenocrysts in a fine-grained matrix of intergrown phlogopite and diopside with minor chrome spinel, perovskite, potassian titanian richterite, barite and apatite. Small xenoliths of deformed, granular dunite are common; most of the xenocrystic olivine is probably derived from disaggregated dunite. Lherzolite xenoliths appear to be rare. The tuffaceous kimberlitoids contain abundant olivine and magmatic fragments in a poorly sorted matrix of detritus derived from magmatic kimberlitoid. Tuff breccias are also present and contain abundant quartzitic country rock fragments.

The leucite lamproites contain phenocrysts of phlogopite, olivine, and/or leucite in a lamprophyric-textured groundmass of leucite, titan-phlogopite, diopside, potassian titanian richterite, apatite, barite, and priderite. Coarse-grained lamproite from Walgidee Hill also contains Sr-rich perovskite, wadeite, shcherbakovite and jeppeite. Pyroclastic rocks, agglomerate, tuff, and lapilli tuff, together with autolithic breccia and tuff breccia are common.

Most intrusions are deeply weathered and many are deuterically altered; olivine is commonly replaced by serpentine, nontronite, celadonite or chalcedony, and leucite is almost invariably replaced by K-feldspar. Carbonate veining is widespread in a number of bodies; other common secondary minerals include zeolite and montmorillonite.

Mineral Chemistry

Xenocrystal olivine compositions in the kimberlitoids lie in the range Mg_{91-93} ($Mg=100Mg/(Mg+Fe)$) and groundmass/microphenocrystal olivine is Mg_{90-91}. Xenocrystal olivine in the leucite lamproites lies in the range Mg_{90-91}, whereas the phenocrysts range to more Fe-rich compositions, Mg_{83-90}. Phlogopite shows a wide range in composition from pale coloured Mg- and Al-rich phenocryst cores (Mg_{91-92}, 22-23% MgO, 10-12% Al_2O_3, 5-6% TiO_2) in the more mafic lamproites to strongly coloured Ti-Fe rich types (Mg_{70-80}, $\leq$30% FeO, 8-10% TiO_2, 1-3% Al_2O_3) present as rims on phenocrysts and in the groundmass. Groundmass phlogopite in individual kimberlitoids also shows extreme compositional ranges (2-12% Al_2O_3, 1-7% TiO_2). Diopside, rich in Ti (1-2% TiO_2) and poor in Al (<0.85% Al_2O_3, mostly <0.5%) is present in the groundmass of the kimberlitoids, and occurs as microphenocrysts and in the groundmass of the leucite lamproites. Potassian titanian richterite (2-6% TiO_2, 4-7% K_2O) is common in the groundmass of both kimberlitoids and lamproites, and is particularly abundant in the more evolved lamproites. Chrome spinel occurs in kimberlitoids and the more mafic lamproites. The spinels range from ferroan aluminous magnesiochromites (8-12% Al_2O_3, <1% TiO_2, $Cr/(Cr+Al)=0.55-0.85$) through rare titaniferous magnesian aluminous chromite (1-4% TiO_2, 10-11% Al_2O_3, $Cr/(Cr+Al)=0.8-0.9$) to titaniferous magnesian chromite (3-6% TiO_2, <10% Al_2O_3, $Cr/(Cr+Al)\geq0.9$). Ulvospinel-magnetite apparently does not occur, presumably because of the crystallisation of priderite which is present in almost all the lamproites examined. Minerals normally considered to be characteristic of kimberlite, including pyrope garnet, chrome diopside (1-2% Cr_2O_3) and ilmenite, have been found in bulk samples of kimberlitoid but are rare. The pyrope is rich in Cr (~7-8% Cr_2O_3, 6% CaO) whereas the ilmenite is mostly of Mg-poor composition ($\leq$8% MgO); Mg-poor ilmenite also occurs in some of the more mafic lamproites. Enstatite Mg_{92-93} (~1.5% Al_2O_3) is very rare.

Geochemistry

The leucite lamproites are characterised by extremely high K_2O (up to 12% with $K_2O \lesssim Al_2O_3$), TiO_2 (3-8%) and BaO contents, and very low Na_2O contents (Wade and Prider, 1940; Prider, 1960). They show a wide range in MgO and SiO_2 contents (3-15% MgO, 45-60% SiO_2), and most follow an orenditic differentiation path of increasing silica saturation, coupled with increasing TiO_2 and K_2O contents.

In contrast, the kimberlitoids have much higher MgO contents (15-28% MgO), have MgO/K_2O ratios signific-antly greater than unity (typically 4-6, cf $\lesssim 1$ for the leucite lamproites), and have lower SiO_2, TiO_2, Al_2O_3 and K_2O contents than the lamproites. Ni and Cr contents in the kimberlitoids are higher than those in the lamproites, typically 600-1000 ppm Ni, 1000-1500 ppm Cr.

Both the lamproites and the kimberlitoids are extremely enriched in 'incompatible' elements, typic-ally containing >750 ppm Zr, >75 ppm Nb, $\gtrsim$5000 ppm Ba, $\gtrsim$200 ppm Rb, $\gtrsim$20 ppm Th, $\gtrsim$200 ppm La and $\lesssim$300 ppm Ce. Both the kimberlitoids and the lamproites have extremely fractionated REE patterns, typical of kim-berlitic rocks in general. LREE abundances in the lamproites range from 600-2000 x chondrites whereas the kimberlitoids range from 500-1000 x chondrites. Contents of Nb are higher, and Zr/Nb ratios lower (<10, cf $\sim$10), in the kimberlitoids than the lamproites.

It is concluded that the leucite lamproites are alkalic (potassic) basic rocks whereas the kimberlit-oids are alkalic ultrabasic rocks resembling kimber-lite.

Relationship between leucite lamproites, kimberlitoids and kimberlites

Diamond has been found in both the kimberlitoids and the leucite lamproites, implying a similar, deep-seated origin for the suite as a whole. The similar-ities in mineralogy and geochemistry of the two rock types and their close spatial association also favours a genetic relationship. Observed differences are thought to be due to fractionation (cf. Prider, 1960).

In general, the West Kimberley kimberlitoids have a similar chemistry to 'typical' kimberlites but their SiO_2, K_2O and TiO_2 contents are higher and their CaO contents lower. However, there are several important mineralogical and petrographic features which combined indicate that the kimberlitoids are not 'typical' kimberlite. These include the rarity of garnet and picro-ilmenite, the presence of groundmass amphibole, the apparent absence of primary carbonate, and the close association with leucite-bearing rocks. These features are consistent with equilibration at lower pressures and, possibly, higher temperatures than 'typical' kimberlite.

Since economic diamond-bearing kimberlites have so far been restricted to cratons which have not been deformed since the Precambrian the discovery of diamond in kimberlitic rocks of unusual composition and in leucite-bearing basic rocks in a shelf environ-ment, outside the craton, has important implications for diamond exploration. If, as we suspect, the rich Argyle pipe in the East Kimberley district proves to be of similar composition to the kimberlitoids of the West Kimberley then clearly a new class of potentially economic diamond-bearing rocks exists.

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H6 KIMBERLITE – LAMPROITE CONSANGUINITY

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The discovery of kimberlites associated with lamproites, both containing diamonds, in the West Kimberley, Western Australia (Atkinson, 1982 and pub. comm) has prompted investigation of the implied genetic relationship. However, lamproites embrace a range of rock types which we demonstrate, using the Spanish occurrences, can have different origins.

The term lamproite was used by Niggli (1923 and subsequent publications) within his classification scheme based on Niggli norms, for volcanic rocks rich in K and Mg. Subsequently, Tröger (1935) stated that lamproite was the effusive equivalent of lamprophyres rich in K and Mg. However, no rocks were described under this heading in Johannsen's (1938) comprehensive petrographic classification. Following Tröger (1935), Wade and Prider (1940) adopted the term for the Australian occurrences (which are mostly minor intrusions) and made the following subdivisions - fitzroyite, cedricite, mamilite, wolgidite and wyomingite. All but latter were new (see also Prider, 1960) and were described as differentiated members containing combinations of phlogopite, leucite, clinopyroxene, magnophorite (K-richterite) with commonly altered olivine.

The Spanish occurrences (Borley, 1967) - termed lamproites by Fuster et al.(1967) - consist of fortunite, verite and jumillite and contain sanidine (or K bearing glass) unlike the Australian rocks, together with clinopyroxene, phlogopite and apatite with or without orthopyroxene, olivine, amphibole, leucite, plagioclase, calcite and quartz. Xenoliths include sporadic mantle-type spinel lherzolites.

Even allowing for the range of petrographic types within each lamproite group it can be seen from the Table below that the Spanish lamproites have a relatively low K_2O/Na_2O ratio and TiO_2 content but with higher Al_2O_3. Of the minor elements, Nb (33ppm) and Zr (571ppm) are significantly lower than in the Australian rocks (150 and 942 ppm respectively).

| wt% | Spain | W. Australia | | S. Africa |
	Lamp.(15)	Lamp.(9)	Kimb.(3)	Kimb.(80)*
SiO_2	54	52	37	36
TiO_2	1.4	5	3.5	1
Al_2O_3	10	7	4	3
Fe_2O_3	6	7	8	8
MgO	10	8	16	17
CaO	5	4	6	11
Na_2O	1.5	0.6	0.4	0.4
K_2O	6	8	3	1.5

*Gurney and Ebrahim (1973)

Numbers of samples analysed given in parentheses.

A major problem in Western Australia is the petro-graphic differentiation of rocks of kimberlite affinity which may be altered and contain serpent-inised olivine (reflected by increased MgO content) and which may also contain deep seated xenoliths and
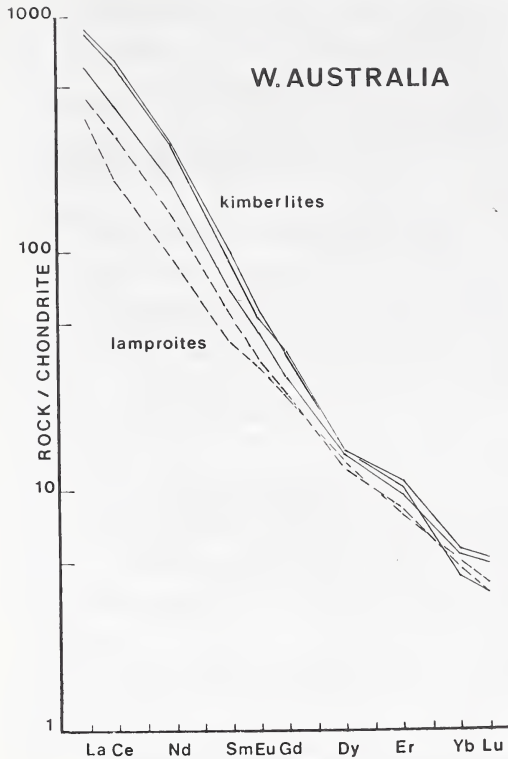
FIGURE 1. *REE patterns showing relative light earth enrichment of Western Australian kimberlites compared with the associated lamproites. (Analyses by I.C.P. analyst : F. Buckley).*

diamonds. Three such rocks, see Table above, are undersaturated and lower in alkalis relative to the lamproites, and are chemically closer to accepted kimberlite composition.

Rare earth data obtained by I.C.P. (Walsh et al, 1981) are used to study the relationship (Fig.1). Australian lamproites show La/Yb ratios which are clearly "kimberlitic" but which, nevertheless, are lower than in associated kimberlites which are heavily enriched in LREE. Both suites are high in Ba (up to> 2 wt%) and Sr (800 - 1800 ppm). The kimberlites have Rb/Sr ranging between 0.27 - 0.52 (lamproites 0.17 - 0.32) see also Powell and Bell (1970), Cr 651 - 886 ppm (297 - 465 ppm and a single result of 1133 ppm), Ni 557 - 1240 (262 - 722), and Nb 203 - 260 (118 - 185). These results show a wide range but have a distinct common imprint. Further evidence of consanguinity is provided by the Nd isotope data given below:

	PHN	$^{143}Nd/^{144}Nd$	Sm/Nd	Nd	$\varepsilon_{Nd}*$
Lamproites	3808	.512143+ 7	.145	61	-9.4
	3812	.511974+ 12	.118	95	-12.7
	3817	.512068+ 19	.123	93	-10.9
Kimberlite	3826	.512004+ 12	.113	130	-12.1
	3829	.511979+ 13	.105	186	-12.6
	3833	.512249+ 15	.110	188	-7.3

*There is some controversy about ages of the W. Australian rocks. A new age for the Howes Hill (west) fitzroyite determined by D.C. Rex (K/Ar = 19 m.y.) agrees with the 17-21 m.y. ages reported by Wellman (1973) and 20 m.y. is used in our calculations. For comparison a hypo-thetical age of 200 m.y. would make PHN 3808 $\varepsilon_{Nd} = -7.0$.

These data suggest that both suites have been derived from a (common) strongly enriched sub-
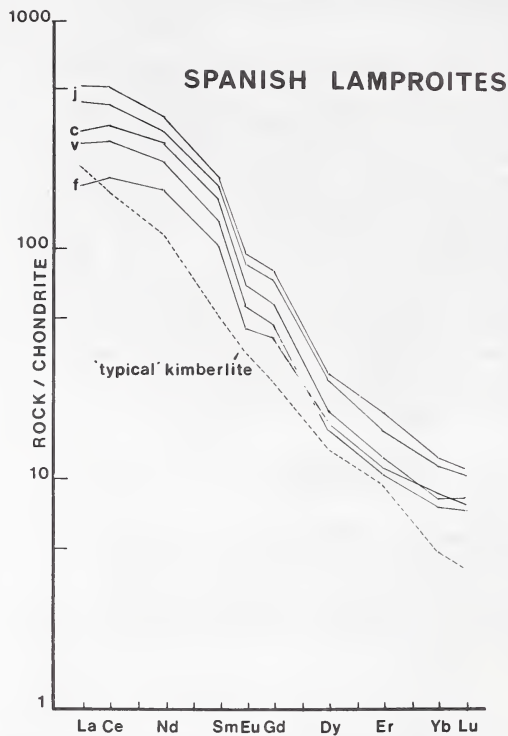

FIGURE 2. *Selection of Spanish lamproite data illustrating a close relationship between fortunite, f; verite, v; cancarix type, c; and jumillite, j. Compared with kimberlites light rare earth enrichment is not sustained for La and Ce, and there is a negative Eu anomaly, reflecting significant genetic differences compared with the Australian kimberlites and lamproites.*

continental mantle. If they plot on the mantle array (De Paolo and Wasserburg, 1979; O'Nions et al, 1979) then $^{87}Sr/^{86}Sr$ ratios of 0.7067 may be anticipated (even this figure is substantially lower than the range, in W. Australian lamproites, recorded by Powell and Bell, 1970).

Further isotope studies are required to evaluate the effect of crustal contamination of
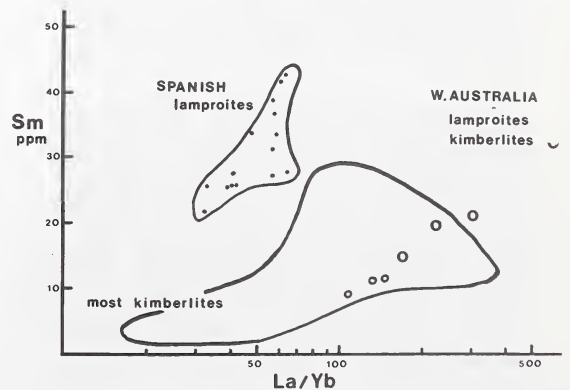

FIGURE 3. *Summary of the La/Yb ratios versus Sm for Australian and Spanish lamproites, compared with kimberlite data mainly obtained from Rogers (1979).*

the magma(s) or post emplacement alteration of the rocks by circulating groundwater (Barrett and Berg, 1975).

The Spanish lamproites show marked REE differences from the W. Australian suites and from "typical" kimberlites (Figs. 2 and 3). The REE pattern could be interpreted to indicate magma derivation from a more depleted source than that of kimberlite but with a similar (metasomatic) overprint of LREE and incompatible elements. The comparatively high HREE content suggests derivation from shallower mantle depths than that in which garnet is stable and correlates with observed lherzolite xenoliths containing spinel rather than garnet. A -ve Eu anomaly persists through the jumillite, cancarix-type, verite and fortunite suites. This feature may be due to removal of plagioclase from the magma or be present in the source region, particularly that of the metasomatising fluids (cf. Hawkesworth and Vollmer, 1979). It is another reason for regarding the Spanish rocks as genetically distinct from the Australian lamproite - kimberlite suite.

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H7   MEGACRYSTS FROM THE HAMILTON BRANCH KIMBERLITE PIPE, KENTUCKY: DISCRETE NODULES AND CUMULATE ROCKS

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The southeasternmost kimberlite pipe in Elliot County, Kentucky, the Hamilton Branch pipe, contains a wide variety of mantle-derived material. Garnet lherzolites and Cr-poor discrete nodules (terminology of Eggler et al, 1979) are most abundant. Also present is a group of cumulate rocks with "discrete nodule" characteristics and fine-grained intercumulus material. This group has been termed the Na-rich suite, based on the high Na_2O content of the diopside.

Monomineralic garnets, diopsides, and ilmenites dominate the Cr-poor suite. Enstatite, olivine, and phlogopite are rare due to near surface weathering. Large olivines are absent, though mosaic dunites are considered members of the Cr-poor suite, based on rare association with Cr-poor garnet and diopside. There is no overlap in olivine composition of dunites (Fo 88-89) and garnet lherzolites (Fo 89.5-93).

The simple concept of magnesian, ilmenite-free discrete silicates distinct from an Fe-rich "ilmenite association" (of lower T, based on Ca/(Ca+Mg+Fe) of cpx) does not apply to this suite. Ilmenite is present throughout almost the entire compositional range of each silicate (Fig. 1) and its composition is related to its texture. Five textural groups of ilmenite-bearing discrete nodules have been recognized: (1) monomineralic ilmenite nodules, generally with porphyroclastic to mosaic texture, (2) ilmenite-dominated nodules similar to (1) but containing small silicate inclusions, (3) silicate dominated nodules, with tiny included ilmenite, (4) Na-rich suite nodules (see below), and (5) graphic cpx/ilm intergrowths. Except for (4) these seem to form a chemically coherent suite.

The Kentucky ilmenites are magnesian (8-15.2% MgO) and rich in ferric iron (6-16 mole % Fe^{+3}) and approximately form a parabolic curve (Haggerty, 1975) on a Cr_2O_3/MgO plot (Fig. 2). However, the low Cr_2O_2

"trough" is displaced to a higher value (12% MgO) than in many other suites. This parabola is comprised of segments corresponding to the five textural groups. Silicate-dominated nodules (3) fall on the Mg, Cr-rich limb, ilmenite-dominated nodules (2) fall in the trough, and graphic cpx/ilm intergrowths (5) bridge the two. The MgO-poor limb is exclusively monomineralic ilmenites (1), which are also found throughout the curve. Approximately 40% of the samples in this group are more iron-rich (Mg/(Mg+Fe) < 0.38) than any ilmenites associated with silicates. Ilmenites from nodules not related to the Cr-poor suite (the Na-rich suite and an ilmenite garnet lherzolite (2.7% Cr_2O_3, 15.5% MgO) also plot on this parabola.

Silicates of Group 3 are as magnesian (and subcalcic in the case of cpx) as ilmenite-free silicates (Fig. 1). Those from ilmenite dominated nodules (2)
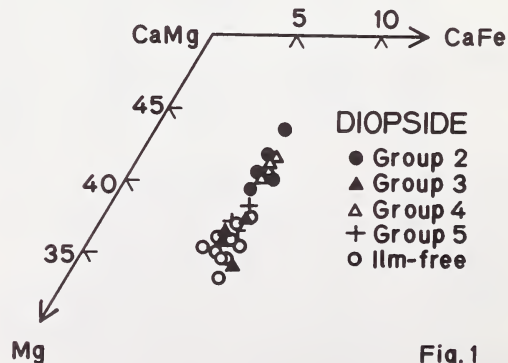

Fig. 1

show Fe-enrichment only slightly greater than analy-
tical uncertainty. Schulze and Hoover (1982) have
shown that precipitation of ilmenite exerts strong
control on megacryst fractionation trends, even to
the point of causing Mg-enrichment. The almost con-
stant Mg/(Mg+Fe) trend (Fig. 1) is therefore probably
due to precipitation of abundant ilmenite. This is
consistent with the observation that ilmenite is pre-
sent throughout almost the entire range of silicate
compositions.

Three groups of discrete phlogopite have been iden-
tified. Two are iron-rich (Mg/(Mg+Fe) = 0.86-0.88)
and are separated by TiO_2 content (0.5-0.6 wt% and
1.3-1.6 wt %). The third group is magnesian (Mg/(Mg+
Fe) = 0.914) and TiO_2-poor ($\sim$ 0.4 wt%). In one sam-
ple of this group the mica is attached to a low T
diopside (Ca/(Ca+Mg) $\cong$ 0.50) poor in Al_2O_3 ($\sim$ 0.3 wt%)
and rich in Cr_2O_3 ($\sim$ 1.9 wt%). Also included in this
diopside is K-richterite, chromite (Cr/(Cr+Al) = 0.94,
Mg/(Mg+Fe) = 0.32), abundant serpentine after olivine,
and calcite and phlogopite-bearing polymineralic in-
clusions of the type Schulze (1981) considered to rep-
resent liquid inclusions, and be indicative of an ig-
neous origin for the host. Neither of the iron-rich
groups has been definitely linked with the Cr-poor
nodules. The affiliation of the Mg-rich group is also
uncertain, although similarities exist with both the
MARID suite (amphibole + phlogopite + diopside assem-
blage and low Al_2O_3 content of the diopside) and the
Cr-rich suite of discrete nodules (high Cr_2O_3 content
of diopside and presence of chromite).

The Na-rich suite consists of aggregates of large
(> .5cm) diopside, ilmenite, and lesser garnet and
orthopyroxene with cumulus textures and fine-grained
intercumulus material (olivine, serpentine, phlogopite,
aluminous pyroxenes, spinel, kaersutite). Represen-
tative compositions are presented in Tables 1 and 2.

Table 1

Analyses of Na-rich suite

	Cpx	Opx	Ga	Ilm
Na_2O	3.52	0.24	-	-
MgO	15.15	33.87	20.66	13.64
Al_2O_3	4.44	0.96	22.90	1.16
SiO_2	55.15	56.92	41.83	0.15
CaO	16.46	0.41	3.52	-
TiO_2	0.41	0.19	0.34	53.63
Cr_2O_3	0.96	0.15	1.07	1.24
MnO	-	0.15	0.42	0.35
FeO^*	4.15	6.64	9.56	30.24
Total	100.24	99.53	100.30	100.41

Table 2

Analyses of intercumulus minerals and bulk

	Amph	Phlog	Sp	Cpx	Opx	Ol	Bulk
Na_2O	2.36	0.26	-	0.96	0.25	-	0.8
MgO	14.62	18.04	22.05	13.62	30.82	47.89	20.9
Al_2O_3	15.38	14.94	60.57	7.46	2.96	-	8.0
SiO_2	40.25	38.51	-	49.44	54.89	39.63	40.1
K_2O	1.76	9.41	-	-	-	-	1.6
CaO	11.25	-	-	22.14	1.28	0.15	5.6
TiO_2	5.86	8.48	0.92	1.90	0.46	-	1.9
Cr_2O_3	0.29	0.54	1.96	0.26	0.68	-	0.3
MnO	0.18	0.10	0.18	0.20	0.18	(0.3NiO)	-
FeO^*	6.57	6.31	14.46	4.40	7.08	11.31	9.1
Total	98.52	97.49	100.14	100.39	98.61	99.28	88.3

The cumulus phases are distinct from garnet lherzolite
minerals, Cr-rich and Cr-poor discrete minerals, and
megacrysts from other alkalic rocks. (Though Boyd and
Nixon (1973) described a similar rock (1680B) as a
cumulate, they did not report intercumulus material).
The diopside is chemically the most distinctive cumu-
lus mineral in its high Na_2O content (3.5-4% Na_2O).
The garnet is characterized by its low TiO_2 and CaO
contents (0.3, 3.5%), and, while the enstatite is as
magnesian as some lherzolite opx's (mg $\sim$ .905), it has
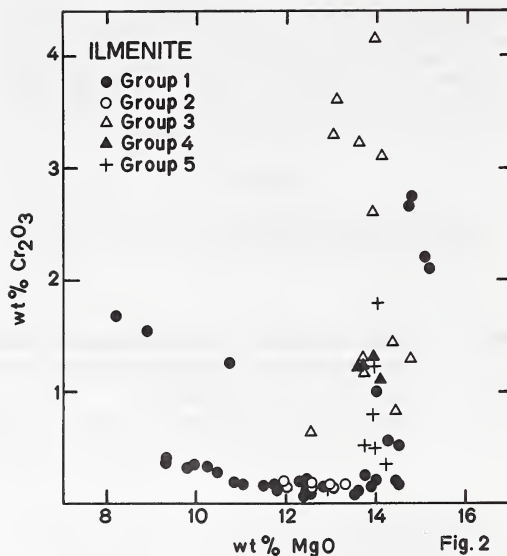Ti > Cr, unlike those from lherzolites. The ilmenites

Fig. 2

form a small cluster on the parabola near MgO 14%,
Cr_2O_3 1.2%.

Though broadly similar to kimberlites in bulk
composition (broad beam probe scan), the intercumu-
lus material is notably higher in Na and Al (Table
2). Mineralogically it is quite unlike kimberlites.
Though the phlogopite is aluminous, it is very high
in TiO_2. The kaersutite is also Ti and Mg-rich,
more so than most kaersutites from alkali basalt
occurrences. Kaersutite is almost unknown from kim-
berlites (Boyd et al, 1981); Ti-poor pargasites and
richterites are the rare kimberlitic amphiboles. The
spinel is unusually Al-rich and Ti-poor for kimber-
litic spinels. The aluminous pyroxenes (up to 12wt%
Al_2O_3 in cpx) are unusual, as is the apparent ab-
sence of calcite. This alkaline ultrabasic liquid
may be a deep-seated lamprophyre.

Equilibration temperatures from Lindsley and
Dixon (1975) and pressures from opx alumina isopleths
of Perkins and Newton (1980) have been estimated for
appropriate assemblages. Discrete Cr-poor diopsides
(± ga, ilm, ol) have the highest temperatures (1400°
C-1290°C), followed at successively lower T's by de-
formed garnet lherzolites (1330°-1270°C), graphic
cpx/ilm intergrowths (1330°-1270°C), both overlap-
ping the discrete diopsides, the Na-rich suite (1210°
-1145°C), tiny cpx's in ilmenite (1210°-1100°C), and
the coarse garnet lherzolites (1150°-1090°C). Esti-
mated pressures fall in a very limited range (45-50
kb) for all cpx-opx-ga assemblages (garnet lherzoli-
tes and Na-rich suite).

The coarse garnet lherzolites represent a "steady
state" at about 1100°C and 45-50 kb. These are
interpreted to have been intruded by a higher T ($\sim$
1200°C) alkalic ultrabasic magma which differentiat-
ed in place yielding the Na-rich suite of cumulates
and a residual intercumulus magma. Like the coarse
lherzolites, these cumulates are essentially unde-
formed. The Cr-poor discrete nodules crystallized
in a sequence similar to that proposed for the
Lekkerfontein suite (Robey and Gurney, 1979), where
initially only silicates precipitated, followed by
graphic clinopyroxene/ilmenite intergrowths, and then
ilmenite-dominated nodules. The final stage, not
recorded in silicate compositions, is the precipita-
tion of abundant iron-rich ilmenite. The Kentucky
suite differs from this, and most other suites, in
having ilmenite present throughout the range of sili-
cates and, therefore lacking the strong iron-enrich-
ment of low temperature nodules. The overlap of
higher T deformed lherzolites and Cr-poor discrete
nodules may imply heating of the wall rock (garnet
lherzolite) by an intrusive magma which crystallized

the Cr-poor discrete nodules. However, a straight-forward transformation of coarse → deformed → Fe-Ti enriched deformed lherzolites is not probable because some of the deformed lherzolites are more magnesian than some of the coarse ones. Hence the relationship of coarse and deformed lherzolites and Cr-poor discrete nodules is still uncertain.

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H8   COMPOSITIONAL AND TEXTURAL FEATURES OF PERIDOTITE NODULES FROM THE JAGERSFONTEIN KIMBERLITE PIPE, SOUTH AFRICA

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Examination in the field of large (>8.0 cm) nodules at a variety of locations around the Jagersfontein mine area reveal that about 80% are coarse-grained peridotites with no obvious fabric or modal layering. The majority of these nodules are close to being harzburgites with only traces (in hand specimen) of other phases, though there are transitions to peridotites with ca. 5% clinopyroxene and/or garnet. Dunites, pyroxenites and ecologites form together about 5% of large nodules. The remainder (ca. 15%) of the large nodule population is essentially formed by deformed peridotites (porphyroclastites or flaser gneisses in hand specimen), which differ modally from the coarse peridotites in commonly being garnet-lherzolites with conspicuous (>5%) clinopyroxene and garnet. Counts of small nodules (<8.0 cm) show a higher proportion (ca. 35%) of deformed peridotites, but maintain the bias to harzburgitic assemblages in coarse peridotites and to garnet-lherzolites amongst deformed peridotites.

Coarse Peridotites

Microscopic and chemical-analytical investigations show that many of the coarse peridotites have detailed petrological affinities to one another. Olivine and orthopyroxene are always the dominant modal phases, but minor amounts of: clinopyroxene, garnet, amphibole, and chromian spinel also commonly occur. Often only two of these additional minerals occur as primary phases, but all combinations have been found including the six-phase assemblage: olivine + orthopyroxene + clinopyroxene + garnet + amphibole + Cr-spinel. A feature of many coarse nodules is the presence in the orthopyroxene of exsolution lamellae of spinel, which may be accompanied by fine birefringent exsolution lamellae (probably of clinopyroxene) and also garnet lamellae. Exsolution lamellae range up to about 0.1mm across. Sometimes garnet, and to a lesser extent spinel, form small grains orientated along grain boundaries and arranged in partial "neck-lets' reminiscent of granular exsolution. Another feature is the occurrence of occasional vermicular intergrowths of clinopyroxene and spinel in some garnet-free rocks.

The amphibole is an edentic hornblende (Leake 1978) and its relatively widespread though not abundant occurrence at Jagersfontein (first reported by Johnston 1973) is unusual by comparison with peridotite nodules from other kimberlites. In general, coarse-nodule mineral compositions are tightly restricted. Some features are shown in Ca:Mg:Fe projection in figure 1. The Al/Al + Cr ratios are: 62-72% in clinopyroxene, 86-90% in amphibole, 90-94% in garnet, and 28-54% in spinel. Mg/(Mg + Fe) ratios in orthopyroxene are 95-91%, and 68-56% in spinel. Al_2O_3 wt% in orthopyroxene varies up to 3.3% in garnet-free assemblages, but is close to 0.65 in garnet-bearing rocks. In two thin sections exsolution lamellae of spinel and garnet in orthopyroxene gave virtually identical compositions to those of independent grains. In the clinopyroxene-
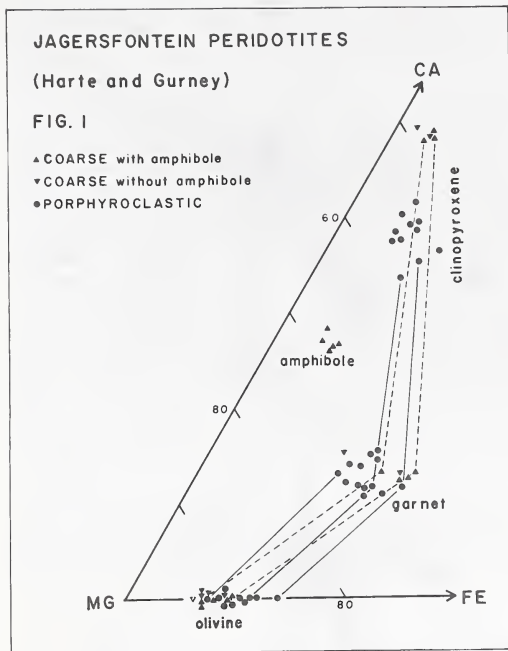
spinel symplectites mineral compositions are also close to those of independent grains, as found in similar intergrowths by Dawson and Smith (1975). One unusual garnet harzburgite shows zoning of olivine and orthopyroxene compositions with variation of 93 to 89.5% Mg/(Mg + Fe) in the olivine, and corresponding variation in the orthopyroxene together with minor increases in Ca and Al. The garnet compositions in this rock are constant, and it is suspected that the rock underwent contamination (or metasomatism) in contact with melt.

The common coarse nodules which appear to form part of a coherent group were probably sampled from a restricted region of the upper mantle. They appear to have originated at high temperatures and cooled very slowly (possibly whilst depressurisation occurred) to allow the exsolution to proceed and the intergrowth compositions to maintain approximate equilibrium with all phases. Ca/(Ca + Mg) ratios in clinopyroxenes are uniformly close to 50% and temperatures indicated by Fe/Mg distribution in coexisting garnet and clinopyroxene (Mori and Green 1978) are in the range 800-875°C. The mineral equilibria had probably become frozen prior to sampling by the kimberlite (Harte and Freer, this volume).

Deformed Peridotites

These nodules fall predominantly into the porphyroclastic and mosaic-porphyroclastic groups of Harte (1977). Some of the mosaic-porphyclastites also show laminar and fluidal textures. Also included in this group are occasional nodules which are transitional between coarse and porphyroclastic textural types, and some which show fine to medium grained granuloblastic textures (perhaps indicating complete recrystallisation and grain growth after deformation). Garnet and clinopyroxene are common phases in addition to olivine and orthopyroxene, but amphibole and spinel have not been found as primary independent phases. However, fine exsolution lamellae of spinel appear to be present within orthopyroxene porphyroclasts in a few nodules.

Mineral compositions are more variable in this group than in the coarse nodules. In addition to the features shown in figure 1 it may be noted that Al/(Al + Cr) varies from 45 to 90% in clinopyroxenes, and from 65 to 97% in garnets. The range of Al_2O_3 in orthopyroxene is however quite restricted between 0.45 and 1.11 wt %; whilst Mg/(Mg + Fe) in this phase varies from 93 to 88%. In most rocks the mineral compositions are homogeneous, but in two cases the olivine and orthopyroxene neoblasts show marginally higher Fe/Mg than the porphyroclasts. Temperature estimates, using Fe-Mg distribution between garnet and clinopyroxene (Mori and Green 1978), show a range of 1140 to 1380°C for the deformed nodules. But some nodules show a lack of correspondence between different geothermometers, which may indicate some disequilibrium. The wide spread of temperature estimates is unusual

JAGERSFONTEIN PERIDOTITES

(Harte and Gurney)

FIG. I

▲ COARSE with amphibole
▼ COARSE without amphibole
● PORPHYROCLASTIC

As partly shown in figure 1 the Mg/(Mg + Fe) mineral compositions of the coarse and deformed perido-tites overlap but with the olivines and pyroxenes tending to have higher Mg/(Mg + Fe) in coarse nodules. Similar relations are seen in bulk rock analyses of the two groups. Another distinction in bulk rock chemistry between the coarse and deformed groups is a tendency for the deformed peridotites to show higher TiO_2 contents. These features correspond to those seen in nodules from other kimberlite pipes (e.g. Gurney and Harte 1980). Derivation of the deformed rocks from originally coarse rocks is indicated tex-turally, and the rare presence of spinel exsolution lamellae in some orthopyroxene porphyroclasts is particularly interesting in that it suggests deriva-tion from relatively low-temperature coarse rocks; perhaps in a process of the type suggested by Gurney and Harte (1980). However, the coarse protoliths for the deformed nodules do not appear to be the rocks represented by the common coarse nodules. This is in-dicated by the modal differences of the two groups of nodules, since the abundance of garnet and clinopyrox-ene porphyroclasts in the deformed rocks makes it un-likely that the modal differences are solely a product of metasomatism.

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by comparison with the limited temperature range at a single kimberlite pipe of many deformed peridotites (group V of Gurney and Harte 1980, Table 1).

H9 CORUNDUM-BEARING GARNET PYROXENITES AT BENI-BOUSERA (MOROCCO): AN EXCEPTIONNALLY AL-RICH CLINOPYROXENE FROM "GROSPYDITES" ASSOCIATED WITH ULTRAMAFIC ROCKS.

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First described by Milliard (1959) the ultramafic Beni-Bousera body (northern Morocco) exhibits spinel-lherzolites and harzburgites associated with spinel and/or garnet pyroxenite layers. The main assemblages belong to the "ariegite subfacies" (O'Hara, 1967) and have been ultimately equilibrated under high pressure granulite facies conditions (10-12 Kbar ; 900°C) together with the surrounding paraderived country rocks, before their tectonic uplift to their present geological environment (Kornprobst, 1969). The various pyroxenite layers have been interpreted as the crystallization products of a melt extracted from the surrounding peridotites during an adiabatic diapiric rise of a fragment of the upper mantle. This interpretation is supported by experimental (Kornprobst, 1970) and geochemical (Javoy, 1970 ; Loubet and Allegre, 1979) data.

The primary crystals precipitated from the melt most generally recrystallized in the solid state but could be recognized and their compositions approximately recalculated ; they appear to be mainly Mg-rich clinopyroxenes involving a large range of Mg-Tschermak solid solution and up to 10% Al_2O_3 contents. A new primary assemblage has been recently discovered, characterized by the presence of corundum associated with Ca-rich garnet and Ca-Tschermak- and jadeite-rich clinopyroxene (Al_2O_3 up to 20%).

I/ THE PRIMARY ASSOCIATION : A CORUNDUM BEARING "GROSPYDITE"

The corundum-bearing rocks have not been found in place and the structural relationships with the peridotites are unknown. They are layered and exhibit sharp compositional variations across a few cm. The
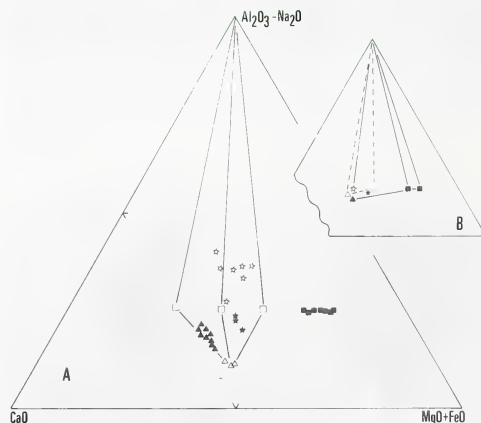

Fig.1: The "grospydites" from the Beni Bou-sera body : solid symbols ; stars = bulk rock compositions ; squares = garnets ; triangles = clinopyroxenes.
1A- Molecules % : comparison with the grospydites from Yakutia (Sobolev et al., 1965 ; 1968); same symbols as above, open.
1B- Weight % : comparison with Boyd's ex-perimental results (1970) ; same sym-bols as above, open.

corundum is visible on hand specimens as small idiomorphic rubies (a few mm long) more or less parallel to the layering. The primary pink garnet is relatively scarce whereas clinopyroxene, as large (1 cm or more) xenomorphic crystals, is the main phase in the rocks. Representative compositions of the primary minerals are given in the Table. More data are plotted in fig. 1.

T A B L E

	bulk-rock	cpx	cpx	gt	co
SiO_2	41.70	45.87	45.75	41.72	0.02
TiO_2	0.35	0.12	0.24	0.05	0.0
Al_2O_3	22.40	19.61	16.78	23.73	99.05
Cr_2O_3	nd	0.0	0.04	0.0	0.21
FeO	4.50	2.44	3.11	8.91	0.38
MnO	0.05	0.05	0.0	0.09	0.0
MgO	10.30	9.28	10.11	16.70	0.09
NiO	nd	0.0	0.0	0.0	0.10
CaO	18.00	20.42	21.42	8.30	0.0
Na_2O	1.60	2.31	1.92	0.03	0.0
K_2O	0.25	0.0	0.0	0.0	0.0
H_2O^+	1.02				
total	100.17	100.11	99.38	99.52	99.92

Analyses of minerals by CAMEBAX probe at
Museum d'Histoire Naturelle de Paris

High Ca-Tschermak and jadeite contents as found in the primary clinopyroxene, and grossular content in the associated pyrope-rich garnet have never been recorded from "eclogites" (ariegites and griquaites) related to the ultramafic bodies, but are known from corundum-eclogites and grospydites, Ca-Al-rich xenoliths associated with kimberlites in South-Africa (Williams, 1932 ; O'Hara, 1966) and Yakutia (Bobrievich et al., 1960). The original grospydites contain kyanite but corundum-bearing rocks have been also described. On the other hand they have a clinopyroxene richer in jadeite and a garnet more calcic (Sobolev et al., 1968) than observed in the rocks at Beni Bousera (fig. 1a).

II/ THE SECONDARY ASSEMBLAGES : CORUNDUM + CLINOPYROXENE UNSTABILITY.

The primary association became unstable during the rock history. Exsolution features in the clinopyroxene (garnet, corundum, spinel, sapphirine and plagioclase lamellae) as well as coronitisations around the corundum crystals underline this unstability. Two main types of coronites have been observed (fig.2) :
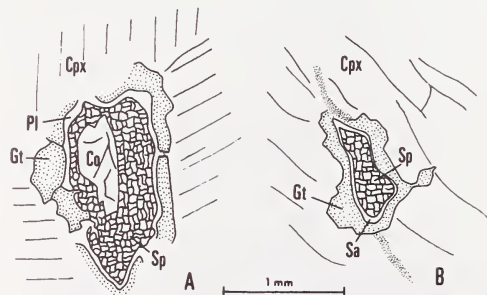

Fig.2: Coronitisation textures around corundum crystals.
2A- Plagioclase-bearing coronite ;
2B- Sapphirine-bearing coronite.

a- The plagioclase-bearing coronites : three envelopes appear around the corundum ; an inner spinel rim is separated from the outer garnet rim by
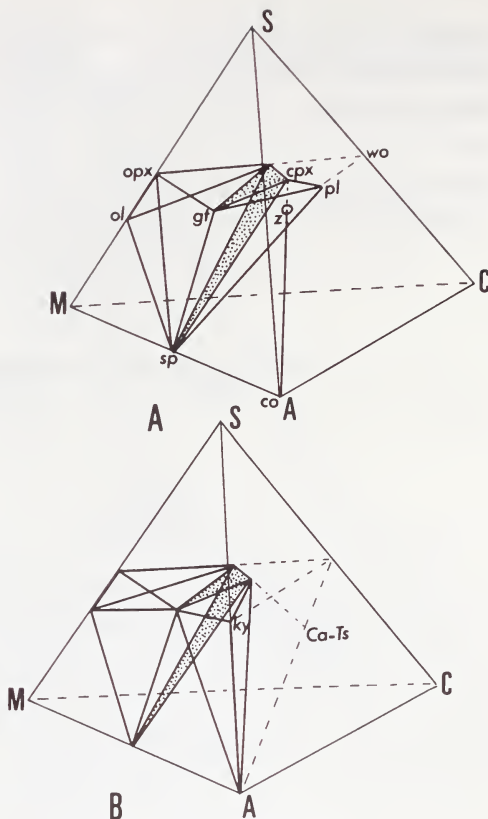

Fig.3: The grospydite subfacies and the reaction : gt+pl+sp $\longrightarrow$ cpx+co.
3A- Al- and Ca-rich garnet-granulites in the ariegite subfacies (cpx+sp+gt+pl). The cpx-co tie line pierces the plane gt-pl-sp in z.
3B- The grospydite subfacies : sp-grospydites (cpx+sp+gt+co) and ky-grospydites (cpx+gt+co+ky).
The dotted surfaces emphasize the griquaites (cpx+sp+gt) volume.

a thin plagioclase rim. It can be interpreted as the result of a reaction :
$$CPX + COR \longrightarrow GT + PL + SP \qquad (1)$$
which can take place on the Ca-Al-rich side of the griquaite plane (fig. 3) at increasing temperature and/or decreasing pressure (Kushiro, 1969 ; Boyd, 1970 ; Thompson, 1979).
b- The sapphirine-bearing coronites : They differ from the former by showing a sapphirine rim instead of the plagioclase zone. This type is not yet fully understood.

II/ CRYSTALLIZATION CONDITIONS OF THE CORUNDUM-BEARING GARNET PYROXENITES AT BENI BOUSERA ("GROSPYDITES" L.S.).

Sobolev et al. (1966) considered that pressures between 20 and 30 Kbar account for the grospydite assemblages and associated kyanite and/or corundum eclogites. Boyd (1970) crystallized a 3 phases association (cpx + gt + cor) at 30 Kbar and 1200 °C, from a glass slightly richer in Ca than the "grospydites" described here (fig. 1) ; a synthetic garnet significantly richer in Ca than the natural one suggests that the experimental temperature was lower and/or pressure higher than the condition experienced by the natural samples. Kushiro (1969) demonstrated that plagioclase disappears from Na- and Ca-rich compositions of the system diopside-anorthite-albite at pressures above 28 Kbar at 1150 °C. Temperatures of equilibration of the

clinopyroxene + garnet pairs can be estimated (Ellis and Green, 1979) : the primary association would have crystallized at about 1325 °C (at 20 Kbar) or 1370 °C (at 30 Kbar).

The crystallization of sapphirine from cor + sp + gt assemblages has been studied in a Fe- and Ca-free system involving water (Ackermand et al., 1975). At temperatures mentionned above the primary association would have crystallized out of the stability field of sapphirine, under pressures as high as 30 Kbar, i.e. in the garnet-lherzolite field (O'Hara et al.,1971): it is time to recall that pressures between 27 and 30 Kbar have been advocated to account for the possible partial melting event in the ultramafic body (Kornprobst, 1970).

Even if the pressure of equilibration of the primary association cannot be accurately determined, it is possible to consider that reaction (1) could play an important role in the mineral facies of the mafic rocks at mantle depth : as clinopyroxene, garnet and spinel are costable on the low pressure side of the equilibrium, this reaction may occur at pressure greater than required for the crystallization of the ariegite association from the reaction :

OPX + PL + SP ⟶ CPX + GT.   (2)

Then, as already suggested by Sobolev et al. (1966), a grospydite subfacies must be emphasized (fig. 3), characterized by the breakdown of plagioclase in Ca- and Al-rich compositions. Because of the lack of reliable experimental data it is not yet possible to define accurately the limits of this subfacies.

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H10 **SULFIDE MINERALOGY AND CHEMISTRY IN SOME FRENCH SPINEL-LHERZOLITE XENOLITHS**

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Sulfides are the only opaque phases present as traces (0,01 to 0,06 %) in the unaltered spinel-lherzolite xenoliths trapped by the alkali-basalts from the Massif Central and Languedoc volcanic suites (120 samples from 23 localities). The sulfides occur mainly as inclusions (10 to 100μ) in the silicates, less frequently as relatively abundant interstitial grains.

Independant of locality, texture (coarse-grained poïkilitic, equant or tabular, porphyroclastic and granuloblastic) and equilibrium temperatures of the parent silicates (900° to 1200°C), the inclusions are composed of the same primary phases : Ni-rich pyrrhotites, pentlandite (Ni/Fe at. rat.~ 1,3) with small amounts of chalcopyrite. Pyrrhotites crystallize in two optically distinct phases, both with the same range of sulphur/metal atomic ratio (M_9S_{10} to M_7S_8) :
  - "grey pyrrhotite" ($Po_{ss}1$), as mono - or polyphase inclusions, showing the highest nickel contents ever found in natural pyrrhotites (20 to 27 weight %), with an average composition (18 inclusions) of $Fe_{36,4} Ni_{23,7} Co_{0,3} Cu_{0,1} S_{39,1}$ wt. % ;

  - "pink pyrrhotite" ($Po_{ss}2$), which shows more variable Ni-contents (7 to 19 wt. %) but is always Ni-poorer than the coexisting $Po_{ss}1$. The "pink pyrrhotite" is always directly associated to the "grey" type, most frequently intimately intergrown, leading to bulk compositions (defocused beam microprobe analyses) which spread in the range (23 inclusions) : Fe : 37-47 ; Ni : 13-24 ; Co : 0,1-0,5 ; S : 38-40 wt. %.

The modal proportions (200 inclusions) show an unimodal distribution between : $Po_{ss}(1+2)$: 70-100 % ; Pn : 0-30 % ; Cp : 0-20 %, giving an average mode : Po_{ss} : 82 % ; Pn : 12 % ; Cp : 6 %.

Phase analysis were done for 45 inclusions, giving bulk compositions with a range : Fe : 33-47 ; Ni : 13-29 ; Co : 0,1-0,5 ; Cu : tr.-7 ; S : 36-39,5 wt. % and resulting in an average bulk pyrrhotite composition (M_9S_{10}) : $Fe_{37,7} Ni_{21,0} Co_{0,3} Cu_{1,6} S_{38,3}$ wt. %.

Experimental phase diagrams in the Fe-Ni-Cu-S system, indicate that such an average composition, as well as the compositions of most individual inclusions, totally crystallized as monosulfide solid solutions (Mss) at 1000°C. The bulk chemical differences observed among the inclusions could be explained by some local differentiations, during deformations, at temperatures between 1000° and 1100°C, where the Mss coexist with more or less Ni and Cu enriched liquids. Present parageneses result from a suite of reactions in the solid state continuing down temperatures between 250° and 300°C, well below those which control the last equili-

Where sulfides are predominant as interstitial grains, their mineralogy and chemistry differ markedly from those of the inclusions, even if both coexist in the same rock sample. In the type suite selected here (Montferrier, Herault), interstitial grains are composed of pentlandite (Ni/Fe ~ 1) associated to a Ni-poor (≤ 0,5 %) pyrrhotite (Fe_7S_8) and minor amounts of chalcopyrite.

Although broadly different from one grain to the other, the mean modal proportions measured in each individual sample (17 inclusions) remain in a relatively restricted unimodal field. Thus, the average mode can be determined to : Po : 47 % ; Pn : 48 % ; Cp : 5 %, with a corresponding bulk chemical composition : $Fe_{45,3} Ni_{16,1} Co_{0,4} Cu_{1,7} S_{36,0}$. These characteristics are believed to result essentially from an early desulphurization of a primary liquid akin to the average composition of the inclusions. This event could have occured during the main episode of deformation and recrystallization of the host rocks, at temperatures between at least 1200° and 1000°C.

The relative sulphur decrease of the pristine interstitial sulfide phase and its differenciation in an open system, may explain both the great modal variation on a small scale and the final crystallization of Po+Pn+(Cp) instead of Po_{ss}+(Pn)+(Cp) at the same low temperature (250°-300°C). It should be noted that both the interstitial and enclosed assemblages are quite different from the sulfide paragenesis due to secondary thermal mobilizations directly related to the basalt eruption.

Most generally, it is concluded that, at least in the area studied, the whole sulfide associations observed in the spinel-lherzolite xenoliths, crystallized directly or were differentiated from a primary homogenous liquid which individualized at high temperatures

T > 1200 °C and is characterized by a relatively high Ni content. Preliminary results show that the same hypothesis can be applied to explain the origin of the sulfide phases in the spinel-lherzolites of the ultramafic bodies from Ariege (French Pyrenees).

H11
SUBSOLIDUS PHASE RELATIONS BETWEEN COEXISTING GARNET AND PYROXENES AT 50 TO 100 kbar IN THE SYSTEM CaO-MgO-AL$_2$O$_3$-SiO$_2$

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Extensive experimental studies simulating chemical compositions of coexisting garnet, orthopyroxene and clinopyroxene of kimberlite xenoliths have been made in the system CaO-MgO-Al$_2$O$_3$-SiO$_2$ (e.g. Boyd,1970; Akella,1976; Parkins & Newton,1980). Most of these studies, however, are in the pressure range below 40 kbar, because of the limitation with the piston-cylinder apparatus. Akagi & Akimoto (1977, 1979) carried out a series of high pressure experiments with a multi anvil type high-pressure apparatus and found that the composition of garnet coexisting with pyroxenes becomes nonstoichiometric (pyroxene-garnet solid solution) above about 50 kbar, and the amount of pyroxene components dissolved in the garnet increases drastically at higher pressures. In order to clarify the thermodynamic nature of the garnet solid solution in equilibrium with two pyroxenes in the pressure range 50 to 100 kbar and formulate geothermometer and geobarometer for kimberlite xenoliths, we have started a series of high pressure experiments. A preliminary result of the experiments is given in this report.

All the experiments were made with a uniaxial split-sphere type multi-anvil apparatus of the Institute for Thermal Spring Research (Ito & Yamada,1982), using graphite heater and pyrophyllite pressure media. In order to improve the thermal gradient across the experimental charge, a graphite heater with 5° taper (2.2 mm average I.D., 3 mm O.D., and 11 mm length) was designed (Takahashi et al, 1982). Experimental run temperatures are believed to be within 20°C to the measurements by the Pt/Pt-Rh thermocouples with the aid of the tapered heater. Two types of starting materials were employed; 1) EWC, which is a glass of enstatite 72.5 mol %, wollastonite 20.0%, corundum 7.5%; and 2) EDP, which is a mixture of synthetic enstatite, diopside and pyrope crystals equivalent to EWC in bulk chemical composition. Both the charges were encased in a Pt-tube (0.9 mm O.D., 2 to 3 mm length) and 0.1 to 3.0 wt % of H$_2$O was added prior to welding the Pt. Experimental run products were sectioned prallel to the length of the furnace assembly and the thin sections were examined with an electron microprobe X-ray analyzer.

Reversal experiments have been made at 1400°C and 75 kbar (Fig.1) and it was found that pyroxenes crystallized from both the starting materials give identical chemical compositions. Garnets started from the crystalline mixture (EDP) are chemically zoned but the rim compositions are very close to those from the hydrous glass (EWC). The compositions of coexisting garnet, orthopyroxene and clinopyroxene crystallized from EWC at other P/T conditions are shown in Fig.2.

Fig.2

gornet lherzolite, Lesotho
gronulor
sheared

Gros   Pyp

Wo   En
Di

○ 100 kb, 1500°C.   △ 75 kb, 1400°C   ◇ 50 kb, 1400°C
▲ 75 kb, 1200°C   ◆ 50 kb, 1200°C

Fig.3   Al$_2$O$_3$ wt%   Opx

Fig.1

HY811219
75 kb, 1400°C, 3.3hr

Gros   Py

Wo   En
Di

starting materials, ○ EWC, ● EDP

Fig.4   Al$_2$O$_3$ wt%   Cpx

The amount of pyroxene components dissloved in the garnet solid solution becomes greater as pressure increases (about 2 mol % at 50 kbar, 9 mol % at 75 kbar and 20 mol % at 100 kbar). The ratio of grossular to pyrope molecules in the garnet solid solution decreases as temperature increases. The net amount of pyroxene components dissolved in the garnet solid solution, however, seems to be relatively insensitive to temperature at a given pressure. The composition of garnet obtained at 75 kbar and 1200°C in the CMAS system is slightly enriched in grossular component than that of a natural garnet lherzolite run at the same P/T condition by Akaogi & Akimoto (1979).

Alumina contents of ortho- and clinopyroxenes coexisting with garnet are shown in Fig.3 and Fig.4, respectively. Alumina isoplethal lines for the pyroxenes were drawn in accordance with the reversed experimental results of Parkins & Newton (1981) at 20 to 40 kbar and 900° to 1100°C. The dT/dP slope and the

Fig.5
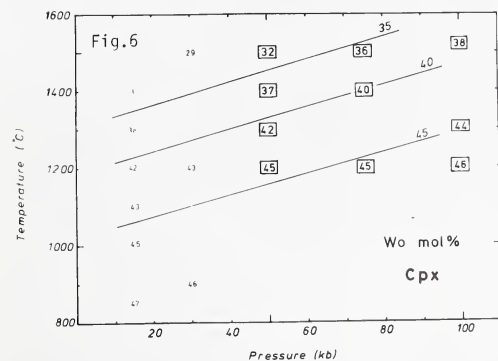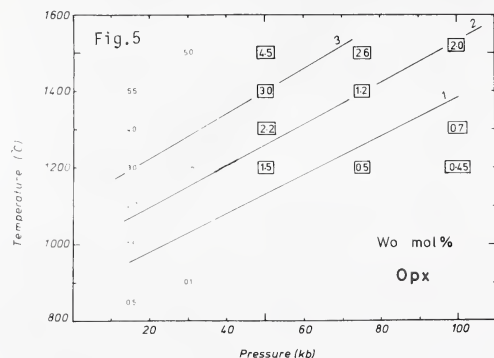
location of the isoplethal lines for orthopyroxene are in harmony with the estimation by Parkins & Newton but are not consitent with those of Akella (1976). The dT/dP slope of the isoplethal lines for clinopyroxene estimated by Parkins & Newton (broken lines in Fig.4), however, are appeared to be overestimated. In consequence of the gentle dT/dP slope of the isoplethal lines for clinopyroxene, the alumina content of clinopyroxene coexisting with orthopyroxene and garnet in the CMAS system is greater than that of orthopyroxene at pressures above about 50 kbar, whereas it is less aluminous than the latter at 30 kbar (Boyd,1970).

The pressure/temperature dependence of the Wo mol% (defined as $100Ca/(Ca+Mg+0.5Al)$ in the CMAS system) of the coexisting ortho- and clinopyroxenes are shown in Fig.5 and Fig.6, respectively. Because pyroxenes in the present study contains very small amount of Al_2O_3 (Fig.2), the Wo mol % of the pyroxenes in the CMAS system should not be different appreciably from those in the Al-free system. The present results, therefore, are compared with the reversed experimental data in the diopside-enstatite system by Mori & Green(1975) and Lindsley & Dixon (1976) in the pressure range 15 to 30 kbar. The pressure effect on the pyroxene solvus (Mori & Green,1975) is confirmed to be present at least up to 100 kbar in the light of the present results (Fig.5, Fig.6), and it follows that the equilibrium temperature estimation from the pyroxene solvus cannot be made without knowing the pressure of equilibration.

Given above observations, sheared garnet lherzolite xenoliths from Lesotho kimberlites (Nixon & Boyd,1973) are considered to have derived from the pressure range 50 to 70 kbar, whereas the granular garnet lherzolites from the same area may have originated at pressures below 50 kbar. The inferred pressures for the sheared lherzolite xenoliths are higher than the estimations by the previous authors (e.g. Boyd,1973; Parkins & Newton,1980).

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Fig.6

H12 CHEMICAL AND ISOTOPIC CHARACTERISATION OF UPPER MANTLE METASOMATISM IN PERIDOTITE NODULES FROM THE BULTFONTEIN KIMBERLITE

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Further major, trace element and Sr-isotope measurements, together with new REE and Nd-isotope measurements, have been made on samples from a much larger peridotite suite than that studied previously[1,2]. For present purposes the suite has been divided into garnet peridotites (GP) which contain no texturally equilibrated or "primary" phlogopite, garnet phlogopite peridotites (GPP), phlogopite peridotites (PP) and phlogopite K-richterite peridotites (PKP). The latter two groups contain no garnet, while diopside may or may not be present in all four groups. The above sequence was previously considered[1] to represent one of progressive mantle metasomatism, culminating in the devel-

opment of K-richterite. However, in view of the greatly increased number of PP rocks now obtained, which appear to have been essentially harzburgitic in original composition, it is questionable whether garnet removal was involved or is essential in the development of the PP and PKP groups. Most samples studied are coarse grained peridotites, with deformed textures being much more common in the GP and GPP groups. However three PKP samples have deformed textures in which both phlogopite and K-richterite have been involved in the deformation process, indicating that these minerals formed before kimberlite emplacement. Additional PKP samples include many more veined examples in which the

veins consist dominantly of K-richterite, usually enc-
losing corroded diopside, phlogopite and opaque oxides
including Ba-K-Zr-Sr-rich titanate[1], attesting to the
chemical nature of the infiltrative metasomatism. Some
angular PKP samples have K-richterite-rich coatings on
bounded surfaces, suggestive of vein infilling in cra-
cks and fractures; although this may suggest that meta-
somatism has occurred on a localized scale, the K-rich-
terite in the veined samples is not confined to the
veins. Also, other larger samples which are not veined
contain sparse texturally equilibrated K-richterite,
indicative of subsolidus replacement. Microprobe major
element   analyses of metasomatic minerals from both
veined and unveined samples provide no real evidence
for chemical disequilibrium except for Cr, and thus the
textural and mineralogical evidence indicates that the
metasomatism has both occurred and attained local equi-
librium on at least the scale of the samples studied.

Major and trace element data support previous concl-
usions about the depleted nature of all samples with
respect to basaltic constituents such as Ca and Al, and
their enrichment in incompatible elements, consistent
with ideas that these samples represent mantle which
has undergone basaltic removal prior to metasomatic en-
richment[1,3]. Incompatible mantle enrichment generally
increases in the sequence GP-GPP-PP-PKP, with the deg-
ree of enrichment varying as shown in Table 1.

Table 1 : Average enrichment factors for incompatible
elements, normalized against nominal mantle concentra-
tions. Number of samples in brackets.

	Rb	Ba	Nb	K	Sr	Zr
GP (9)	4.5	4.9	7.0	2.3	3.1	1.1
GPP (11)	19	23	16	15	7.7	2.4
PP (7)	73	30	12	49	5.8	2.8
PKP (22)	115	25	34	62	10	10

It is noteworthy that even the least metasomatised
GP samples show incompatible element enrichment rela-
tive to the nominal mantle composition; however, the
effects of possible kimberlite contamination are lik-
ely to be most apparent in these samples, since they
lack primary mica or amphibole. While there is a gener-
al similarity in incompatible element enrichment in the
other three groups, differences are apparent as shown
most clearly by the Ba-Rb plot presented in Fig 1.
(dashed line is Ba/Rb ratio for nominal mantle).

Fig. 1
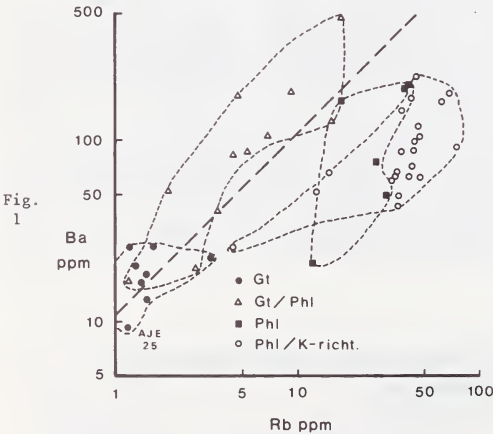
The distinction between the GP and GPP groups on
the one hand, and the PP and PKP groups on the other
cannot be due to original mineralogy and must reflect
either two chemically distinctive metasomatic process-
es or a more complex situation (multi-stage) which
must involve a systematic decrease in the Ba/Rb ratio
of the metasomatising fluids with progressive metasom-
atism. The latter is demanded if the four peridotite
groups are metasomatically related [1]. REE data pre-
sented in Fig. 2 show that all samples are enriched
in LREE, but with the PKP group showing greater rela-
tive LREE enrichment, in view of their greater HREE
depletion.(note that the PKP data suggest that alkali
basalts and kimberlites could be produced from such a
source without the necessity of involving garnet con-
trol).

Interpretation of the combined mineralogical, tex-

tural and chemical data follows conventional wisdom
in assuming that amphibole-bearing samples are derived
from shallow mantle depths. Our suggestion that gar-
net removal was not involved, or at least not

Fig. 2
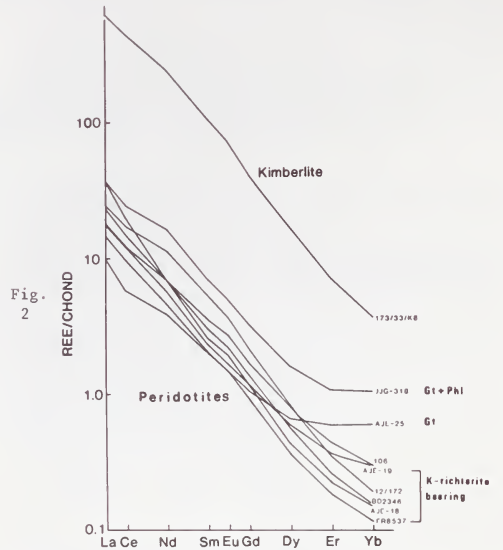
essential, in the development of the PP and PKP groups
is substantiated by the REE data. We infer that the GP
and GPP groups were metasomatised at greater depths
than the PP and PKP groups, the original source rocks
for the latter being more refractory (Al-poor harzbur-
gite) in composition. The metasomatic fluids at the
time of metasomatism were chemically distinctive but
it is not yet possible to typify their source(s). The
isotope evidence is now considered in order to further
evaluate this question, the role of kimberlite activi-
ty, and the timing of metasomatism.

Previous Sr-isotope whole rock data[2] together with
our new data, are shown in Fig. 3.

Although the new data show more scatter, they conf-
irm the conclusion[2] that metasomatism is unrelated to
kimberlite emplacement at 90 m.y., since all but two
samples have distinctly higher initial $^{87}Sr/^{86}Sr$ ratios
than the kimberlite at that time. The data allow an ea-
rlier association between some of the metasomatised sa-
mples and the (proto) kimberlite, or its source, in the
upper mantle at 150 m.y., but further evaluation of the
whole rock data is best assessed by reference to Sr-
isotope data obtained on mineral separates, HCl leached
whole rocks and minerals and associated leach solutions,
and different portions of the same rock. General ob-
servations from three PKP rocks are : (i) K-richterite
and/or diopside - phlogopite tie lines yield ages close
to 90 m.y., indicating approximate isotopic equilibrium

Fig. 3
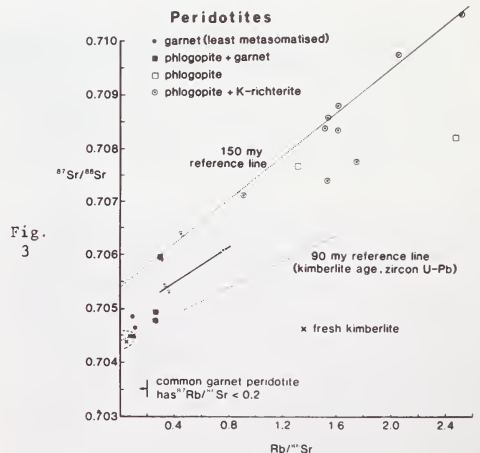
at pipe emplacement (ii) progressively leached phlogo-
pite fractions from the same separate show a dramatic
increase in $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$, consistent with
removal of calcite lamelli, but still define an age of
87 m.y., (iii) whole rock initial ratios are generally
lower than for diopside or K-richterite, (iv) differ-
ent portions of the same rock are not in isotopic equ-
ilibrium (see three circled points joined by a solid
line in Fig. 3) and (v) leaching of one whole rock
yielded a leached residue with a higher initial $^{87}Sr/$
^{86}Sr ratio (.70546), and a leach solution with a lower
initial ratio (.70503) than the original rock (.70525).

Summary of the above suggests that while the major
Rb and Sr hosts, phlogopite, diopside and K-richterite
are in approximate isotopic equilibrium, the rocks an-
alysed also contain (exotic?) components with un-equi-
librated strontium. These could be fluids of kimberl-
ite origin (cf. "secondary" phlogopite selvedges arou-
nd garnets in GPP rocks) since mixing plots ($^{87}Sr/^{86}Sr$
vs 1/Sr) show that this is not due to the simple add-
ition of the kimberlite itself. Rocks with lowest Rb
and Sr would be most affected; least metasomatised GP
rock AJE25 [2] has an inital ratio of .70473 while its
diopside has an initial ratio of .70512, in support of
the above contention. Thus, while some samples shown
in Fig. 3 may have had their $^{87}Sr/^{86}Sr$ ratios decreased
slightly during kimberlite emplacement, the overall
scatter is considered to be a consequence of mantle
metasomatism which has affected all the peridotites
analysed. This is emphasized by diopside analyses,
which show high and variable $^{87}Sr/^{86}Sr$ ratios (Fig.4)
and Sr contents, 200-1000 ppm Sr [2]. The metasomatic
fluids appear to have had variable $^{87}Sr/^{86}Sr$ ratios and
Sr contents and while it is possible to infer a chemi-
cal distinction in terms of Rb/Sr between the garnet-
bearing and garnet-free peridotites, no clear distinc-
tion can be made regarding the timing of metasomatic
event(s). The significance of the 150 m.y. reference
line in Fig.3, considered [2] to be related to the cess-
ation of Karoo igneous activity, remains an open ques-
tion, and must be viewed in context with the Nd-isotope
data presented in Fig. 4.

The $^{143}Nd/^{144}Nd$ data confirm the enriched nature of
the peridotites, consistent with previous data for
peridotite diopsides [3], compared with present day
Bulk Earth (intersecting lines in Fig.4), kimberlites
[4, this study] and diopside megacrysts [4]. The lower
$^{143}Nd/^{144}Nd$ ratios of peridotite diopsides, reported
as being separates from the GPP group, with respect
to the PKP rock data for a given $^{87}Sr/^{86}Sr$ value (Fig.
4), might suggest that the former indicate an earlier
metasomatic event than inferred for the PKP data, bas-
ed on consideration of Nd model (CHUR) ages. However,
the most "enriched" diopside has now been found to be

Fig. 4
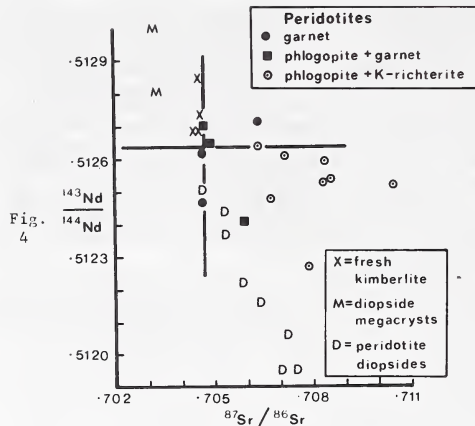
from a PKP, and not a GPP, rock. $^{143}Nd/^{144}Nd$ data for
this rock, two other GPP rocks and associated diopside
and mica analyses [3] are as follows :

Sample	Type	Rock	Diopside	Phlogopite
CK26	GPP	.51265+2	.51223+2	.51185+7
CK27	GPP	.51270+2	.51250+3	.51224+10
CK32	PKP	.51227+1	.51195+4	-

The implied disequilibrium, together with the proxim-
ity of CK26 and CK27 to the kimberlite data (Fig.4)
suggest that, as with Sr, the whole rocks contain un-
equilibrated Nd of kimberlite origin. Nevertheless,the
relatively low $^{143}Nd/^{144}Nd$ ratios in rock CK32,coupled
with the even lower ratios in its diopside (and the
phlogopites), suggest an earlier age of metasomatism
than indicated by the Sr-isotope data, and it is poss-
ible that rock CK32 may contain two mantle metasomatic
age components. More detailed isotopic work is clearly
required before the timing of mantle metasomatism and
the mantle differentiation events (melting, plume act-
ivity, subduction) possibly involved in the production
of the metasomatic fluids, can be defined.

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Erlank, A.J. and Shimizu N., 1977 : Ext. Abst., 2nd
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H13

VOLUME INSTABILITIES IN THE MANTLE AS A POSSIBLE CAUSE FOR KIMBERLITE FORM

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The occurence of kimberlites and their mode
of formation are evidence for punctual instabi-
lities in the mantle which lead to the build-
up of extremely high fluid pressures in an al-
kali-rich, mostly potassic environment. The
geological setting points at the mantle under-
neath stable shields. The driving force is
provided mainly by CO_2 with additional H_2O,
but the gases contained in fluid inclusions,
for instance in diamonds, are varied. They
comprise hydrocarbons, alcohols, oxygen, nitro-
gen, and others.
    In order to understand kimberlites and kim-
berlite formation it is essential to gain an
insight into the dynamic processes which occur
under the confining pressure of the mantle. Ob-
viously these processes are related to the pre-
sence and to the local accumulation of dissolved
fluid phases. Hence, it is important to under-
stand their dissolution mechanism, to know what
solute species might form and what their role
could be in the temporal evolution of a poten-
tial kimberlite source region.
    The usual approach followed by petrologists
is to analyze the phases present in a given

rock and to relate these findings to experimen-
tal data from high pressure laboratory studies.
It is well known that carbonates and hydroxyl-
bearing phases precipitate from CO_2- and H_2O-
rich magmatic systems. It has therefore been
concluded that carbonate ions, CO_3^{2-}, and hydro-
xyl ions, OH^-, are the prevalent solute species.
This view has recently been challenged (FREUND
1981a and references cited therein) by the dis-
covery of solute carbon in synthetic MgO and in
natural, mantle-derived olivine which is not car-
bonate but a novel carbon species characterized
by a valence state near zero and by a special
nature of the chemical bond with the surrounding
oxygens. The name "atomic carbon" has been coined
for such dissolved carbon species which formally
derive from the CO_2 dissolution mechanism.
    The "atomic carbon" dissolved in oxides and
silicates has unusual properties, both chemical
and physical unlike any carbonate carbon. The
"atomic carbon" is capable of reacting with the
lattice oxygen to give CO_2 or CO depending on
experimental parameters. With the hydrogen de-
rived from lattice-bound OH^-, i. e. from the
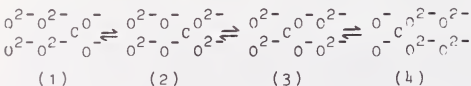dissolution mechanism of H_2O, this carbon re-

acts to give a wide variety of hydrocarbons, saturated and non-saturated, including aromatic compounds. With molecular H_2O it reacts to give alcohols; with co-dissolved nitrogen to give HCN, amines, and other complex C-N compounds. With the silicon of the silicates it may form Si-C bonds. With the cations, for instance with Mg^{2+} and Fe^{2+} in olivines, it reacts to give volatile metal-bearing organic compounds (FREUND et al. 1982).

The physical properties of the "atomic carbon" are equally outstanding and in sharp contrast to what one would expect for carbon from carbonate ions.

The diffusion of the "atomic carbon" is extremely fast even in such densely packed structures like MgO and olivine. The diffusion coefficient data which are now available cover the temperature range from $-100^{\circ}C$ to $700^{\circ}C$ WENGELER et al. 1982; KATHREIN 1982; KATHREIN et al. 1982; OBERHEUSER 1982). They indicate that the "atomic carbon" may be the fastest diffusing species in mantle rocks. Its motion is endowed with a negative activation volume of diffusion. This is nothing else but the mathematical expression for the fact that the CO_2 dissolution increases with hydrostatic pressure (BROWN and ASHBY 1980). Indeed, the CO_2 solubility rocks, both solid and liquid, increase quite dramatically above 10-20 kbars, corresponding to a depth range of 30-60 km, i. e. to the lower crust and/or upper mantle. At the same time, however, "atomic carbon" diffuses in response to stress, both microscopic and macroscopic, from regions of high stress to regions of low stress. Grain boundaries represent no diffusion barriers for the "atomic carbon", because it can convert reversibly to CO_2 and back to dissolved carbon at the grain-to-grain interface.

By combining the available physico-chemical data with the general concept of plate tectonics we are led to consider long-range carbon diffusion as a very realistic geological possibility. This carbon diffusion is expected to occur at or below the crust/mantle boundary from regions of high compressive stress to regions of tensile stress or stress shadow zones. It may transport a large flux of "atomic carbon" over distances of hundreds or thousands of kilometers within, geologically speaking, short to moderately long times.

The nature of the "atomic carbon" cannot be fully apprehended, unless one understands the process of charge transfer (CT) by which carbon becomes reduced to the essentially zerovalent state and oxygen becomes oxidized from the O^{2-} state to the O^- state (FREUND 1981b). Any O^- represents a defect electron in a given oxide or silicate structure. This O^- state is the companion of the "atomic carbon" and remains associated with it during diffusion. The $C-O^-$ bond is quite energetic, strongly covalent but at the same time spatially delocalized. This is because every neighboring O^{2-} can become an O^- by a mere electron exchange. Thus, when the "atomic carbon" diffuses, defect electrons travel along, probably two per C atom. In a very schematic way we may represent this as follows:

$$O^{2-}_{}O^{2-}_{}C^{0}_{}\rightleftharpoons O^{2-}_{}O^{-}_{}C^{0}_{}\rightleftharpoons O^{2-}_{}C^{0}_{}O^{2-}_{}\rightleftharpoons O^{-}_{}C^{0}_{}O^{2-}$$
$$O^{2-}_{}O^{2-}_{}O^{-}_{}\quad O^{2-}_{}O^{-}_{}O^{2-}\quad O^{2-}_{}O^{-}_{}O^{2-}\quad O^{-}_{}O^{2-}_{}O^{2-}$$

$$\quad(1)\qquad\quad(2)\qquad\quad(3)\qquad\quad(4)$$

During steps 1/2 and 3/4 two electrons move from left to right while the C atom executes one diffusional jump from right to left between step 2/3.

Thus, during the postulated long-range diffusion of "atomic carbon" an electron flux of equal magnitude is anticipated to occur in the opposite direction. If the "atomic carbon" accumulates in a given stress shadow zone somewhere in the mantle, this also means an accumulation of O^-, i. e. of defect electrons.

The O^-, if taken separately, are capable of forming dimers, trimers and possibly tetramers which are resonance-stabilized to various degrees through their interaction with the sur-

rounding O^{2-} and with the atomic C. When the P, T-conditions change in a certain way such as expected for a diapiric uplift environment, both experimental data (KATHREIN 1982) and theoretical considerations indicate that the O^- stabilization breaks down. Such a breakdown is accompanied by an efflux of defect electrons, because the O^- tend to reconvert to O^{2-}. One of several possible consequences of this process is an influx of electrons from the surrounding mantle to account for the $O^- \rightleftharpoons O^{2-}$ conversion.

In such a case the mantle volume under consideration will (a) increase in volume, because the partial molar volume of O^{2-} is considerably larger than that of the O^-, and (b) acquire a differential negative charge due to the electron influx. As a result of the latter positive charges, viz. cations, will be drawn in concomitantly in order to maintain electroneutrality.

This process is essentially electrochemical. We propose to call it "electrochemically driven metasomatism". Depending upon the nature and the availability of the positive charges in the surrounding mantle and/or in the overlying crust the cation influx can be either predominantly H^+, Na^+, K^+. In any case the melting temperature will decrease, probably to a dramatic extent. The volume will increase. The pressure, both internal and that exerted on the surrounding rock, will rise. The ultimate consequence of this process is an instability in the mantle which is self-catalyzing and self-amplifying (FREUND 1981c).

If an electrochemically driven metasomatosis as outlined here develops deep in the mantle where K^+ dominates, a kimberlitic magma can be generated. It is expected to propagate towards the surface of the Earth. During the depressurisation the charge transfer (CT) processes which provide the basis for O^- formation and their reconversion to O^{2-} will become accelerated. As soon as CO_2 gas forms, two electrons per CO_2 molecule are released. The final stage is an explosive discharge of the highly potassic, CO_2-driven magma. This magma is expected to be in an unusual physical state best described as plasma-like, adiabatically cooled, but characterized by electronic CT processes which are still in progress in the fluidized solid and which will eventually be quenched by an influx of H^+ from meteoritic water leading to a late-stage serpentinisation.

In summarizing we can say that the mechanism of kimberlite formation and eruption outlined here derives from a mechanism - novel for geology - of interatomic electronic charge transfer (CT) occuring in solids as a function of P and T between oxygen as electron donor and electropositive electron as acceptors. Its background is well-founded theoretically since a long time and it has been studied in detail experimentally for the CO_2 and H_2O solubility in MgC and in mantle-derived silicate minerals such as olivine. The attractive feature of the CT mechanism and of its sequential evolution through various stages is that it leads to an entirely novel concept of magma genesis without violating, at any step, known physico-chemical principles. The kimberlite magma genesis represents an extreme case.

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H14 METASOMATISM IN THE MANTLE BENEATH PIPE 200, NORTHERN LESOTHO

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Introduction

Peridotite nodules in kimberlite contain
information about the equilibria or disequilibria
that prevailed in the mantle just prior to eruptio
If a nodule shows signs of physical (textural) or
chemical disequilibrium, then information may
potentially be obtained on two or more processes
which had affected the mantle in the vicinity of
its origin, including the timing of those events.
This is the case with a small number of nodules
from Pipe 200, including some described by Carswel
et al. (1979) and Mitchell et al. (1980).

The Pipe 200 (PTH) nodules consist of garnet
lherzolite, garnet-chromite lherzolite, chromite
lherzolite and spinel harzburgite. The rocks
generally have low modal percentages of clino-
pyroxene and garnet, low Al_2O_3, CaO and Na_2O, high
100 Mg/(Mg + Fe) values of 91.0-95.4 and high 100
Cr/(Cr + Al) values of 11.6-48.9. These features
are consistent with depletion caused by removal of
a basaltic partial melt from more normal garnet
lherzolite.

Mineralogy and Chemistry of the Altered Samples

Six different peridotite nodules (PTH 108, 202,
204 and 404 of Carswell et al. (1979), plus PTH
58 and 516 courtesy of B. Harte and M.J. O'Hara)
were the subject of further study because of their
unusual mineralogy and the textural associations

involving those minerals. Normal PTH nodules
contain some chrome pyrope garnet, usually with a
rim of fine-grained kelyphite attributable to
rapid alteration in the ascending kimberlite (Fig.
1A). In sample PTH 58 chrome diopside occurs as
rare discrete grains in the rock, but more signi-
ficantly as a collar of grains, with clear cores
and cloudy, pitted margins, around the garnets.
This collar also contains small amounts of phlogo-
pite and tiny euhedral spinels. The garnet may
be partially kelyphitized (PTH 58, Fig. 1B) or
wholly kelyphitized (PTH 404, Fig. 1C). In sample
PTH 204 (Fig. 1D), the collars around a kelyphitized
garnet core are considerably wider, coarser grained,
and both phlogopite and spinel are more abundant.
The clinopyroxene and phlogopite show a mosaic
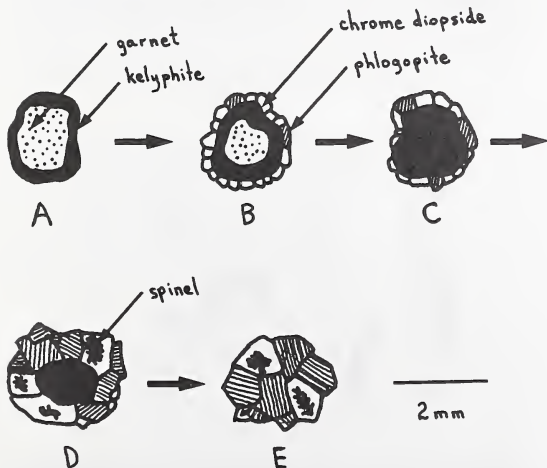
Figure 1

	PTH 58 (COLLAR)			PTH 204 (INTERMEDIATE)		
	CPX	PHL	SP	CPX	PHL	SP
SiO_2	55.22	41.16	–	54.51	40.26	–
TiO_2	–	0.29	0.96	–	0.22	–
Al_2O_3	2.52	13.18	9.45	4.45	14.92	14.8
Cr_2O_3	2.95	1.03	54.08	3.10	1.11	53.7
FeO	2.04	2.60	18.94	1.99	2.31	18.0
MnO	–	–	0.16	–	–	–
MgO	15.95	25.00	13.20	13.60	24.22	13.6
CaO	19.06	–	0.10	19.95	–	–
Na_2O	2.61	1.16	–	3.29	0.80	–
K_2O	–	9.80	–	–	9.83	–
TOTAL	100.35	94.22	96.89	100.89	93.67	100.10

	PTH 108 (POOL)		
	CPX	PHL	SP
SiO_2	54.31	42.48	–
TiO_2	–	0.23	0.73
Al_2O_3	1.28	12.38	5.35
Cr_2O_3	3.11	0.88	59.90
FeO	2.37	2.71	22.61
MnO	0.11	–	0.55
MgO	16.46	26.49	11.10
CaO	20.53	–	–
Na_2O	2.14	–	–
K_2O	–	10.03	–
TOTAL	100.31	95.20	100.24

Table 1.

texture, and the clinopyroxene and spinel often show a symplectic relationship. In addition, the phlogopite shows wavy extinction and some kink banding. Finally, in PTH 108, 202 and 516, garnets are absent and all that remains in their place are pools of coarse-grained phlogopite, chrome diopside, and chrome-rich spinels (Fig. 1E). Phlogopite is generally the most abundant phase, and the chrome diopsides are characterized by clear cores and cloudy rims.

Representative analyses of the collar and pool minerals are summarized in Table 1.

Single pyroxene thermobarometry (Mercier 1980) on the collar and pool chrome diopsides might be expected to show equilibrium conditions different from those obtained for more normal nodules from Pipe 200 (Carswell et al. 1979; Mitchell et al. 1980), but the excess of Na over Al (cations) in these pyroxenes proved to be unsuitable for that particular calculation. The phlogopites of the collars and pools are primary according to the classification of Carswell (1975), and this is interpreted to mean that they are of earlier mantle, rather than of later diatreme, origin.

Collar and Pool Formation

From the textural relations shown in Fig. 1, it is clear that the collars and pools have formed largely at the expense of garnet. Such fertile clots of minerals could not have survived the partial melting event as demanded by the depletion of the whole-rock composition, therefore collar and pool formation post-dated the partial melting event. The coarse-grained texture of the collars and pools, the deformation of the phlogopites and the primary chemical compositions of the phlogopites all suggest that collar and pool formation predated the kimberlite diatreme event. Thus the time of formation of the collars and pools is bracketed between the depletion and diatreme events.

It is possible that the collars may represent the products of the retrograde reaction, olivine +

garnet → opx (grain growth outside the collar) + cpx + spinel, with either decreasing pressure in an ascending diapir, or with decreasing temperature after the partial melting event, or both. However, the presence of minor phlogopite in the collars suggests that metasomatic fluids rich in H_2O and K_2O were at least involved in initiating garnet breakdown. The pools, with up to 80% phlogopite after garnet, are clearly the result of mantle metasomatism, and from the range of textures developed (Fig. 1), this reaction had progressed to different degrees. Although there is no evidence in these samples to help distinguish between the metasomatism-before-magmatism model of Boettcher et al. (1979), and the metasomatism-after-magmatism model of Wyllie (1980), it is believed that the extent of collar and pool formation in the Pipe 200 nodules is more likely a function of the distance of these rocks from a water-saturated magma (either kimberlite, or fractionating to become kimberlite) prior to their incorporation into that magma and rapid ascent to the surface.

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H15 **NATURE OF THE CONTINENTAL UPPER-MANTLE/LOWER-CRUST TRANSITION BENEATH KILBOURNE HOLE, NEW MEXICO**

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Models of the continental upper mantle-lower crust transition zone are principally constrained by the study of xenoliths brought to the earth's surface by basaltic magmas. However, because xenoliths occur in restricted tectonic environments closely associated with basaltic volcanism, they do not necessarily represent a typical sample of the lithosphere but a modified product formed in response to the thermal evolution of such regions. The information obtained from xenoliths is limited by our ability to reconstruct the mechanical and thermal history of the samples. Xenoliths of both crustal and mantle rocks are abundant at Kilbourne Hole and help to constrain the rheology, composition and thermal regime of the crust-mantle boundary beneath the Rio Grande Rift.

Crustal Xenoliths
The crustal xenoliths from Kilbourne Hole point to the existence of a granulite facies metamorphic complex composed of garnet and two-pyroxene granulites, garnet orthopyroxenites, anorthosites and charnockites (Padovani and Carter, 1977). Estimated peak temperatures of 1000-1100°C intimate that the lower crust was partially melted and recrystallized as fine-grained anhydrous granulites. The transient nature of this thermal event is inferred from local mineral disequilibrium (zoning) of the constituent mineral phases, indicating subsequent slow cooling (Padovani and Hart, 1981).

Mantle Xenoliths
The mantle xenoliths include dunites, harzburgites, both members of the Cr-diopside spinel lherzolite
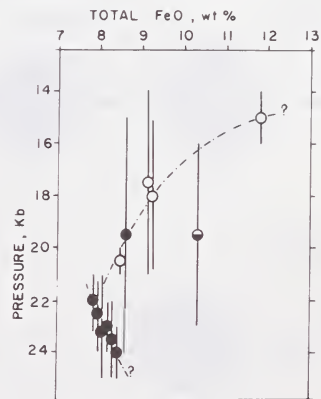

Fig. 1. *Bulk FeO vs. average of two independent barometric estimates for granuloblastic (open circles), protogranular (filled circles) and composite xenoliths.*

suite and the Al-Ti augite suite as well as rare composites and megacrysts. The spinel lherzolites are the most abundant and can be subdivided into two textural types: granuloblastic (fine grained) and protogranular (coarse grained). Both are occasionally cut by spinel pyroxenite veins (composites), interpreted as products of flow crystallization (Irving, 1980). No structural relationship has been observed between the two lherzolite types which are also dissimilar in their bulk chemistry: granuloblastic samples show a wider range in the Mg/Fe ratios of the constituent phases and generally higher bulk Fe and LREE than the protogranular samples (Irving, 1980).

Independent pressure estimates from two separate geobarometric calibrations (Finnerty and Boyd, 1978; Dixon and Presnall, 1980) suggest that the spinel lherzolites were sampled over a large pressure interval (10 kb) and that the most Fe-rich granuloblastic xenoliths are from shallower depths than the more depleted protogranular xenoliths (Fig. 1). Similar relationships have been described by Mercier (1977) for the adjoining Basin and Range and Colorado Plateau provinces which suggest some lateral continuity. In the composite samples, pyroxenite veins cutting the Fe-rich lherzolites are usually at high angles to the foliation when present and are bordered by narrow zones of Fe-poor (depleted) lherzolite. This feature is interpreted as localized partial melting of the host lherzolite (Bussod, 1981) and implies that the Fe-rich composition of the granuloblastic samples predates the intrusive event.

The two lherzolite varieties also differ in the preferred orientations of olivine. The symmetry of olivine fabrics is orthorhombic for both types and is interpreted as resulting from preferential slip on [100] (010), the dominant slip system at high temperatures. However, the olivine fabrics in the protogranular samples are more nearly axial about [010], perhaps the result of a variation in mantle rheology with depth. Olivine fabrics from composite samples are more complex, though their symmetry is also dominantly orthorhombic. Weak girdles about a [010] maximum are typically present and may be due to the formation of pyroxenite or amphibole-bearing veins visible in these samples. This would imply that, unlike the compositional variation, the variety in olivine preferred orientations may be localized to narrow zones affected by the advective transfer of heat from conduit walls.

Olivine-spinel (Fabriés, 1979) and two-pyroxene thermometers (Wells, 1977) were applied to all the lherzolitic assemblages studied. Temperatures derived from the two methods are in good agreement for the protogranular xenoliths and yield apparent equilibration temperatures between 950°C and 1050°C. However, large temperature discrepancies are found using the two methods for the granuloblastic and composite samples (Fig. 2). For these rocks, the spinel is demonstrably out of equilibrium with the silicate phases, but neither this disequilibrium nor the inherent differences between the thermometers can account for such large temperature differences. This is attributed to a recent in situ thermal perturbation (with temperatures up to 1150°C) affecting only the shallower granuloblastic and composite samples. Experimental work on the diffusion rates in spinels (Freer, 1980) and
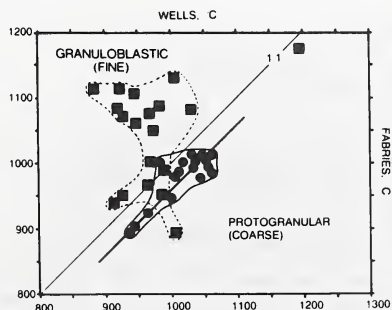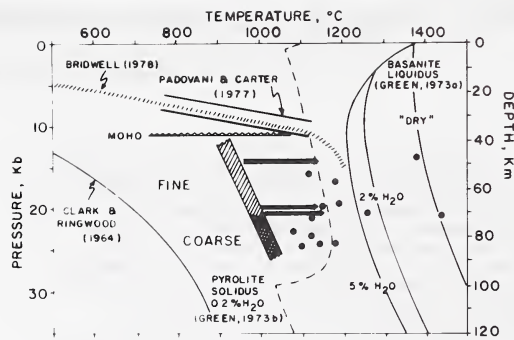
Fig. 3. Mantle and crustal geotherms. Crustal geotherm from Padovani and Carter (1977) and Bridwell (1978). Mantle geotherm, this study. Arrows indicate estimates of reset olivine-spinel equilibration temperatures in granuloblastic samples. Black dots are thermometric estimates from the Ca content of olivine rims using the experimental calibration of Finnerty and Boyd (1978).

examination of the Ca-zoning profiles of the coexisting silicate phases support this hypothesis.

Discussion

The P-T relations obtained from the upper mantle and crustal xenoliths from Kilbourne Hole demonstrate that the lithosphere has been sampled continuously from a depth of 80 km (Fig. 3). The mantle thermal gradient of 10°C/km agrees well with similar determinations for this region (Reid, 1976; Mercier, 1977). Yet is is difficult to connect the 30°C/km crustal gradient geotherm to the upper mantle geotherm. Evidence of a recent thermal overprint in the uppermost mantle can be attributed to the development of a basaltic conduit system prior to and during incorporation and transport of the xenoliths to the surface (Bussod and Irving, 1981). Granulite facies metamorphism of the lower crust can be attributed to the conductive heating from a similar conduit system developed in the upper mantle and/or lower crust during the earlier stages of rifting. The granuloblastic texture in the mantle and fine-grained textures in the crustal rocks developed under a deviatoric stress regime during these local thermal episodes. However, the compositional stratification of the upper mantle probably predates rifting and appears laterally extensive, indicating that a 30 km layer of undepleted dense mantle exists between the lower crust and a depleted residual mantle.

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Fig. 2. Evaluation of thermometric estimates for granuloblastic (squares) and protogranular samples (circles).

H16   LOWER CRUSTAL NODULES FROM THE CAMP CREEK LATITE, CAREFREE, ARIZONA

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A suite of lower crustal mafic to ultramafic nodules collected from the Camp Creek locality (16 km ENE OF Carefree, Arizona) is comprised predominantly of eclogites (Jd/Ts>.8), garnet clinopyroxenites (Jd/Ts<.8), garnetites, and amphibolites. These nodules occur in a potassic latite (6.5%K_2O) which contains phenocrysts of biotite (Mg/Mg+Fe=.6) and clinopyroxene ($Ca_{47}Mg_{41}Fe_{12}$) as well as minor xenocrysts of plagioclase, orthoclase and quartz in fine-grained groundmass of plagioclase, clinopyroxene and oxides. Arculus and Smith (1979) and Schulze and Helmstaedt (1979) described a suite of nodules in a latite from Chino Valley (130 km NNW of Camp Creek) which is strikingly similar to the Camp Creek one (Table 1). However, the latite host at Camp Creek is slightly richer in SiO_2 and K_2O but poorer in CaO than the Chino Valley latite, possibly reflecting different degrees of contamination with the Precambrian basement.

TABLE 1:   COMPARISON OF MAJOR ELEMENT COMPOSITION OF LATITES FROM CAMP CREEK AND CHINO VALLEY (in weight %)†

	Camp Creek*	Chino Valley**
SiO_2	63.07	62.81
TiO_2	0.92	0.94
Al_2O_3	15.20	13.47
Fe_2O_3***	5.39	5.29
MnO	0.06	0.06
MgO	3.15	4.98
CaO	3.62	4.61
Na_2O	2.27	1.66
K_2O	6.61	5.34
P_2O_5	0.36	0.30
	99.41	99.46

†   Analyses recalculated loss-free.
*   XRF analysis by Dr. A. Yeats, Chemistry Dept. Arizona State University.
**   XRF analysis from Schulze and Helmstaedt, 1979.
*** Total iron as Fe_2O_3.

The dominant nodule types at Camp Creek are garnet clinopyroxenite (some with > 50% modal garnet) and Type B eclogites (Coleman et al., 1965). Their mineralogy consists of varying amounts of garnet ($Py_{50-30}Alm_{49-28}Gross_{28-13}$) and diopsidic clinopyroxene (< 13% Jd) with minor amounts of pargasite, apatite, rutile and Fe-Ti oxides. The amphibolites make up to 30% of the suite and are predominantly composed of pargasite and pargasitic hornblende (according to Leake, 1978) with minor garnet, phlogopite, apatite, clinopyroxene, rutile, and Fe-Ti oxides. Whereas the garnet clinopyroxenite nodules are well preserved, the amphibolites contain a variety of alteration products, partial melting textures, and features along the host-nodule boundaries indicative of some reaction with the host lava. Several inclusions contain both eclogite and amphibolite in contact suggesting they coexist at depth and probably grade into one another.

Several geothermometers applied to the various mineral assemblages at P=10kbar indicate equilibration temperatures on the order of 700-900°C (Table 2). However, two samples of Type C eclogites show definite discrepancies. The first, a garnet clinopyroxenite containing 20% modal apatite, yields discordant temperature values. A second sample consisting of the assemblage garnet ($Py_{31}Alm_{45}Gr_{24}$)

TABLE 2:   CALCULATED TEMPERATURES (°C) at P = 10 kb

Sample #	1	2	3	4	Mineralogy*
7549	802	790			eclogite (+am)
7514	747	716			eclogite (+ru)
7520	806	760			eclogite (+am+ru)
7502	803	868			eclogite (+ru)
7503	827	923			eclogite (+ru)
7552	809	704			garnet clinopyroxenite (+am)
7541	695	859			garnet clinopyroxenite (+ap+sp)
7529	810	857	833		amphibolite (+gt+ph)
7535			647		amphibolite (+gt+bt+pl)
7542				720‡	amphibolite (+pl+ph)

1 based on Raheim and Green, 1974.
2 based on Dahl, 1980.
3 based on Ferry and Spear, 1978.
4 based on Buddington and Lindsley, 1964.
* Abbreviations: am = amphibole; ru = rutile; ap = apatite; sp = sphene; gt = garnet; ph = phlogopite; bt = biotite; pl = plagioclase.
‡ calculated fO_2 = 10^{-15} atm.

-plagioclase (An_{51}) -clinopyroxene suggests a maximum equilibration pressure of 8±1.6kbar (assuming a_{SiO_2}=1) based on an experimental geobarometer by Newton and Perkins (1982). These pressure and temperature estimates agree with the equilibration conditions obtained for the eclogite and amphibolite nodules of Chino Valley and suggest high geothermal gradients under these areas. However, the Camp Creek suite apparently does not contain samples of the higher P, T assemblages of websterite and orthopyroxene found in Chino Valley. The larger variety of nodule types of the latter could be a function of the larger areal extent of this locality compared to the Camp Creek area.

The similarity in the chemistry and mineralogy of the nodules and host rocks from both Camp Creek and Chino Valley localities suggest: (1) that these nodules are representative samples of the lower crust under these areas, and (2) that the latite hosts might have had a common petrogenetic history, possibly related to the period of potassic volcanism which affected the western edge of the Colorado Plateau during the Oligocene.

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H17   **PETROLOGY OF THE CRUST/MANTLE BOUNDARY BENEATH SOUTHWEST JAPAN**

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Ultramafic and mafic xenoliths in Cenozoic alkali basalt lavas from Oki-Dogo island in the Japan Sea have been studied. Relative proportion of rock types of the xenoliths in 10 eruptive units was determined in situ (Fig.1) and following systematics were discovered: 1)lavas which contain spinel lherzolite xenoliths always contain all other rock types; 2)proportion of dunite, wehrlite and pyroxenite increases as proportion of spinel lherzolite decreases; 3) there are lavas which contain only gabbros and granulite xenoliths. Spinel lherzolites and other peridotite and pyroxenite xenoliths are distinct in that (1)the latter frequently show mineralogical bandings whereas spinel lherzolites are always massive; and (2)spinel lherzolites show a narrow range of compositional variation (e.g. Fo=90-86, NiO in olivine 3500-4000 ppm) whereas the latter rocks exhibit a wide range of variation (e.g. Fo=87-75, NiO in olivine 3000-500 ppm) (Fig.2).
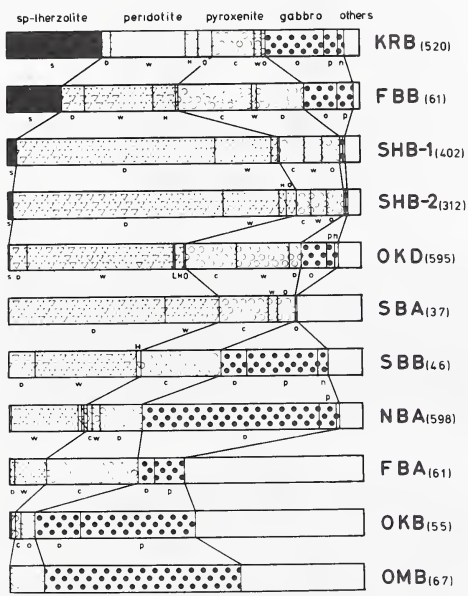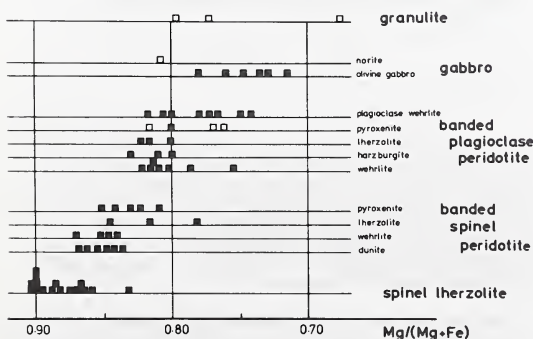
From mineral assemblages the banded peridotites and pyroxenites are classified into two categories: 1)banded spinel peridotite group, represented by the four phase assemblage ol+opx+cpx+sp equivalent to the spinel lherzolites; 2)banded plagioclase peridotite group, comprises the ol+opx+cpx+pl assemblage. Equilibration temperatures by the geothermometer of Wood & Banno (1973) are in the range spinel lherzolite 1100-1200°C, banded spinel peridotite 1050-1100°C, banded plagioclase peridotite 1000-1100°C, gabbro 1000-1100°C and granulite 900-1000°C (Fig.3). The rocks of the banded spinel peridotite group and the banded plagioclase peridotite group are considered to be cumulates from basaltic magmas at pressures above about 10 kbar and below that pressure, respectively. Judging from their metamorphic textures and the relatively low equilibration temperatures, however, those rocks can not be cognate inclusions precipitated from the host magma.

Based on these results a perologic model of the crust and upper mantle beneath Oki-Dogo island is constructed (Fig.4). The lower crust is composed mainly

Fig. 1

Fig. 3

Fig. 2
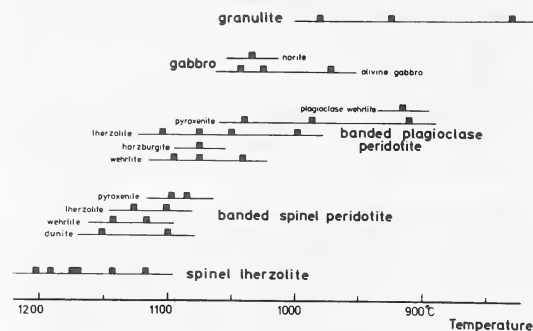
Fig. 4
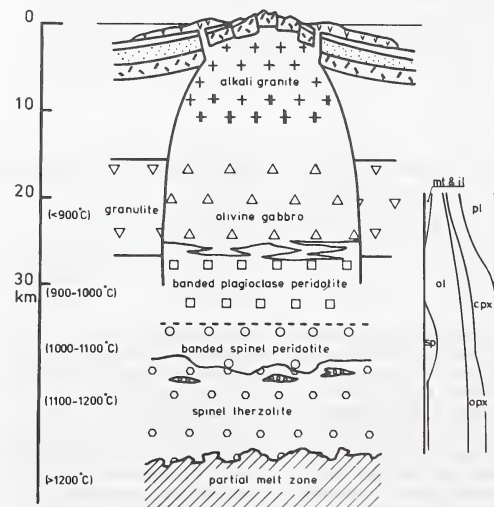
of olivine gabbro and granulite, and the uppermost mantle is composed of thick layers of banded perido- tite and pyroxenite underlaid by a zone of massive spinel lherzolite. The depth from which the host magmas have derived may be different among the erupt- ive units considering the variety and the systematics in the xenolith associations shown in Fig.1. The lavas which contain spinel lherzolites, however, must have derived from the deepest zone of the strata.

High pressure phase relations of a basalt taken from the unit KRB (which contains the largest amount of spinel lherzolites among the 10 units in Fig.1) have been determined (Fig.5) with a piston-cylinder apparatus under dry conditions (Takahashi, 1980). The lava KRB is considered to have last equilibrated with the spinel lherzolite upper mantle at about 40 to 50 km depth and may have ascended without chemical modi- fication, because it coexists with ol+opx+cpx on its liquidus at 14 kbar (Fig.5).

Fig. 6

Fig. 5

Fig. 7
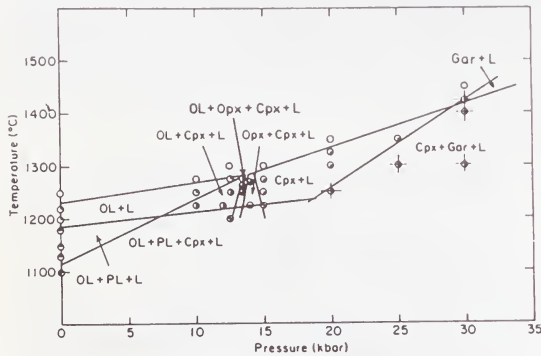
Spinel lherzolite is considered to be the major constituent of the earth's uppermost mantle and the xenoliths of that rock type predominate over other peridotite and pyroxenite in most of the alkali basalt localities in the world (Forbes & Kuno, 1967). How- ever, paucity of spinel lherzolite xenoliths and ex- istence of the large amount of cumulative peridotite and pyroxenite xenoliths are common natures in alkali basalt localities in the Sowthwest Japan (e.g. Yama- guchi,1964; Aoki,1968; Takahashi,1978). The upper- most part of the mantle beneath this area may be oc- cupied with a large amount of peridotite and pyroxe- nite cumulates (Fig.6).

According to Hashizume & Matsui (1979), no sharp reflections from the Moho discontinuity have been observed from this area, and their best fit velocity model (Fig.7) suggests that the crust/mantle boundary beneath this area comprises numerous alterations of mafic and ultramafic rocks such as in layered intru- sive bodies. The crust and upper mantle beneath the
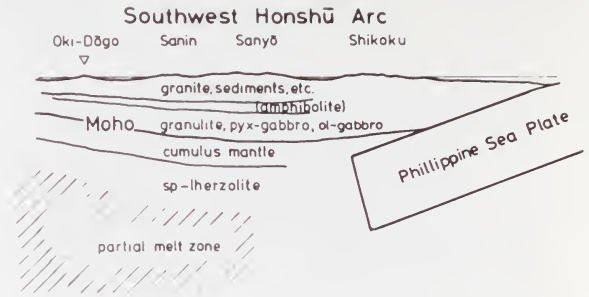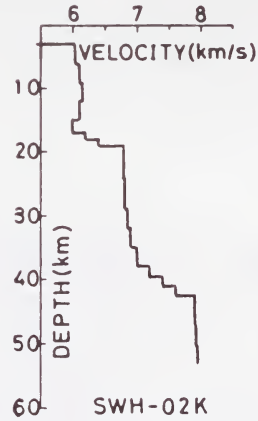
Southwest Japan may have been chemically differenti- ated due to a large flux of magmas during the last 100 Ma period, where and when extensive andesite vol- canisms and granitic batholith formation took place. The bulk chemical composition of the crust above the petrologic Moho (the boundary between the spinel lherzolite layer and the cumulative peridotite/pyro- xenite layer in Fig.4 and Fig.6) could be basaltic rather than andesitic.

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H18 THEORETICAL PREDICTION OF SUBSOLIDUS PHASE RELATIONSHIPS IN PERIDOTITES AND BASALTS

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A considerable amount of experimental and calorimetric data on the thermodynamic properties of pure minerals and solid solutions have been obtained in recent years. These data have been used to calibrate geothermometers and geobarometers (e.g. $CaMgSi_2O_6$ orthopyroxene-clinopyroxene) in an attempt to determine the physical conditions of formation of crustal and mantle rocks. Thus far, however, such approaches have used only a few of the possible components present in multiphase assemblages and, with the exception of the work of Nicholls (1977)

there has been no attempt to calculate the total compositions and stabilities of all possible phases. The object of this study is to predict both phase relationships and mineral compositions as functions of pressure, temperature, and bulk rock composition by integrating available thermodynamic and phase equilibrium data.

The method used to calculate equilibrium assemblages at given P, T and composition is that of free energy minimisation using steepest descent.

This has been employed to obtain an internally consistent thermodynamic data set based on calorimetric and phase equilibrium measurements in the systems
$CaO-Al_2O_3-SiO_2$, $MgO-Al_2O_3-SiO_2$, $CaO-MgO-Al_2O_3-SiO_2$, $Na_2O-Al_2O_3-SiO_2$ and $FeO-MgO-Al_2O_3-SiO_2$.
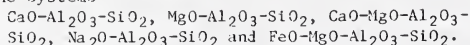
Currently, the following data give good fits to enthalpy, entropy and phase equilibrium data in the CMAS System:

Phase	Component	H(1000K) cal	S(1000) cal K-1
clinopyroxene	$CaMgSi_2O_6$	-34 900	96.7
" "	$CaAl_2SiO_6$	-18 400	97.1
" "	$Mg_2Si_2O_6$	-15 180	94.17
" "	$NaAlSi_2O_6$	-18 100	92.12
orthopyroxene	$CaMgSi_2O_6$	-34 900	96.7
" "	$MgAl_2SiO_6$	+1 920	95.0
" "	$Mg_2Si_2O_6$	-16 820	93.51
spinel	$MgAl_2O_4$	-5 200	64.47
plagioclase	$CaAl_2Si_2O_8$	-24 250	127.8
olivine	Mg_2SiO_4	-14 980	66.23
garnet	$Ca_3Al_2Si_3O_{12}$	-77 510	187.2
"	$Mg_3Al_2Si_3O_{12}$	-20 450	185.9
quartz	SiO_2	0	27.62
corundum	Al_2O_3	0	43.0

Phase	Component	V(298K) c·c	$\alpha \cdot 10^5$	$\beta \cdot 10^6$
clinopyroxene	$CaMgSi_2O_6$	66.1	2.92	0.82
" "	$CaAl_2SiO_6$	63.62	2.7	0.8
" "	$Mg_2Si_2O_6$	62.64	2.92	1.01
" "	$NaAlSi_2O_6$	60.4	2.66	0.75
orthopyroxene	$CaMgSi_2O_6$	66.1	2.92	0.82
" "	$MgAl_2SiO_6$	58.93	2.92	1.01
" "	$Mg_2Si_2O_6$	62.64	2.92	1.01
spinel	$MgAl_2O_4$	39.71	2.75	0.49
plagioclase	$CaAl_2Si_2O_8$	100.79	1.48	1.1
olivine	Mg_2SiO_4	43.79	4.14	0.79
garnet	$Ca_3Al_2Si_3O_{12}$	125.24	2.34	0.54
"	$Mg_3Al_2Si_3O_{12}$	113.3	2.57	0.47
quartz	SiO_2	22.688	6.0	2.5
corundum	Al_2O_3	25.575	2.61	0.37

These data reproduce phase equilibrium measurements on the spinel-peridotite → garnet-peridotite reaction in the systems $MgO-Al_2O_3-SiO_3$ and $CaO-MgO-Al_2O_3-SiO_2$ assuming $\Delta Cp = 0$. In the former system, the reaction passes through the P-T points 20.2kbar/1100°C, 18.3kbar/900°C and 17.5kbar/600°C with the spinel-olivine-pyroxene assemblage being stable on the low pressure side. In the CMAS system, the reaction is calculated to be shifted to pass through points 14.5kbar/1100°C, 14.2kbar/900°C and 15.2kbar/600°C. The reaction: Forsterite + Anorthite = Spinel + Orthopyroxene + Clinopyroxene is calculated to take place at points 7.9kbar/1300°C, 7kbar/1100°C and 6.1kbar/800°C.
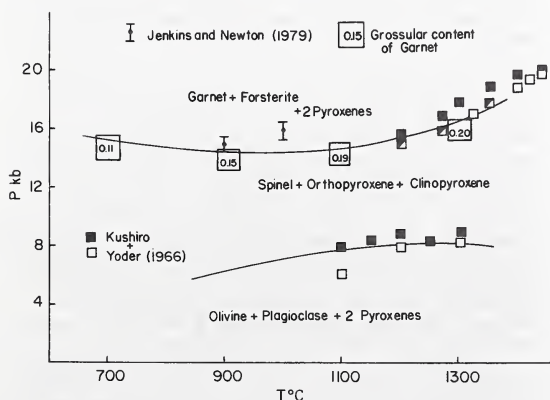
The figure shows calculated positions of facies boundaries in the CMAS system, together with

available experimental data on the reactions of concern. Of particular interest is the shallow positive (~6bar/K) P-T slope of the garnet-spinel reaction at high temperatures and the negative slope at low temperatures. The changeover can be ascribed to the fact that the pyroxenes which are involved in the reaction have much more extensive mutual solubility and higher Al_2O_3 contents at high temperature than at low temperature. The decreasing extent of solid solution with lowering temperature lowers the entropies of the pyroxene phases sufficiently for the high pressure garnet-bearing assemblage to have a higher entropy than the low pressure spinel assemblage at temperatures below 950°C. A similar, but opposite effect can be seen at the plagioclase-spinel lherzolite boundary, the relevant reaction having pyroxene on the high pressure side. Uncertainties in the calculated boundaries mainly arise from uncertainties in the solid solution properties. For example, pyrope-grossular garnets appear, on the basis of calorimetric measurements (Haselton and Westrum, 1980) to have moderate excess entropies. The relatively flat, calculated P-T slope of the spinel-garnet reaction at high pressures is, in part, an artifact of this excess entropy term which stabilizes garnet progressively with increasing temperature. In order to fit the available unreversed data (Kushiro and Yoder, 1966; Herzberg, 1978) better, a steeper slope is required. This can only be achieved with excess entropies close to zero. In addition, the equilibrium garnet composition is calculated to change substantially along the spinel-garnet boundary whereas available data (Jenkins and Newton, 1979, Boyd, 1970) suggest that it should be constant at Ca/Ca+Mg of 0.15.

The effects of Na_2O on the lherzolite reactions may be calculated reasonably well using calorimetric and phase equilibrium data on jadeite and high albite together with activity-composition relations for diopside-jadeite and albite-anorthite solid solutions.

Constraints on the thermodynamic properties of Fe-bearing components ($Fe_2Si_2O_6$, $CaFeSi_2O_6$ etc.) are much poorer than those discussed earlier. Data for such components were dominantly based on phase equilibrium results on the reactions:

Fe_2SiO_4 + SiO_2 = $Fe_2Si_2O_6$
Fayalite   Quartz   Ferrosilite
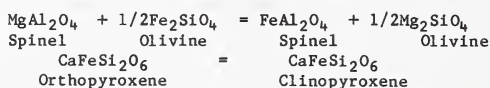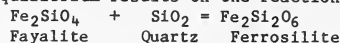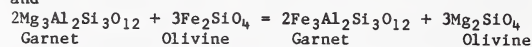
$MgAl_2O_4$ + $1/2Fe_2SiO_4$ = $FeAl_2O_4$ + $1/2Mg_2SiO_4$
Spinel   Olivine   Spinel   Olivine
$CaFeSi_2O_6$ = $CaFeSi_2O_6$
Orthopyroxene   Clinopyroxene
and
$2Mg_3Al_2Si_3O_{12} + 3Fe_2SiO_4 = 2Fe_3Al_2Si_3O_{12} + 3Mg_2SiO_4$
Garnet   Olivine   Garnet   Olivine
together with the calorimetrically measured entropy of fayalite. The following results have been obtained for Na- and Fe-bearing components:

Phase	Component	H(1000K) cal	S(1000) cal K-1
clinopyroxene	$NaAlSi_2O_6$	-18 100	92.12
" "	$CaFeSi_2O_6$	-28 900	105.23
" "	$Fe_2Si_2O_6$	-6 790	110.44
orthopyroxene	$CaFeSi_2O_6$	-27 485	105.23
" "	$Fe_2Si_2O_6$	-7 220	109.94
spinel	$FeAl_2O_6$	-2 720	72.04
plagioclase	$NaAlSi_3O_8$	-15 700	130.11
olivine	Fe_2SiO_4	-6 850	83.47
garnet	$Fe_3Al_2Si_3O_{12}$	-12 780	209.17

Phase	Component	V(298K) c·c	$\alpha \cdot 10^5$	$\beta \cdot 10^6$
clinopyroxene	$NaAlSi_2O_6$	60.4	2.66	0.75
" "	$CaFeSi_2O_6$	67.88	3.9	0.82
" "	$Fe_2Si_2O_6$	65.98	3.9	1.0
orthopyroxene	$CaFeSi_2O_6$	67.88	3.9	0.82
" "	$Fe_2Si_2O_6$	65.98	3.9	1.0
spinel	$FeAl_2O_4$	40.75	2.54	0.49
plagioclase	$NaAlSi_3O_8$	100.43	3.44	1.6
olivine	Fe_2SiO_4	46.39	3.2	0.91
garnet	$Fe_3Al_2Si_3O_{12}$	115.3	2.44	0.53

Preliminary calculations on a model natural peridotite "pyrolite III" indicate that the spinel-garnet reaction is shifted downwards to about 10kbar at 900°C. This result is in good agreement with the experimental data of Jenkins and Newton (1979). Calculations on the gabbro-eclogite reaction in an Fe-rich bulk composition indicate that garnet should appear at 8kbar at 900°C. This is in good agreement with the experiments of Green and Ringwood (1967), bearing in mind the small overpressure (~ 2kbar) required to achieve nucleation of garnet.

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H19 KIMBERLITES OF SOUTHERN AFRICA – ARE THEY RELATED TO SUBDUCTION PROCESSES?

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Although proposed by Sharp (1974) that the Mesozoic kimberlites in Southern Africa originated from activity at the deep end of a subducted oceanic plate, a connection of kimberlites with subduction processes has not been generally accepted. Dawson (1980 p. 220) states that such "hypothesis is contrary to the observed random distribution of kimberlites in Southern Africa ..", and remarks further that " ... the confinement of kimberlite magmatism to the cratonic centers of continents well away from any major fold belts, together with the very limited amounts of kimberlite magma, appear to preclude any connection with classical subduction zones."

However, inspite of recent progress in our knowledge of kimberlite formation and emplacement, the " ... vexing problem of why kimberlites occur, and why they occur where they do has not been solved" (Meyer, 1979). Other plate-tectonic-related hypotheses of kimberlite distribution, such as transform fault models (Williams and Williams, 1977; Stracke et al., 1979) or hot spot models (Hastings and Sharp, 1979; Crough et al., 1980), do not explain the ultimate source of H_2O and CO_2 necessary for kimberlite formation, and we can only speculate whether these volatiles "come from deeper" or from "recycling via subduction" (Wyllie, 1979). While the hypothesis that the volatiles are juvenile gases from the deep mantle provides no means of predicting the location and timing of kimberlite eruptions, the possibility of a causal relationship to subduction can be tested because kimberlites should be localized above remnants of subducted plates. For such relationships to become obvious, the classical view that all subduction zones are steeply dipping and therefore cannot reach far enough under continents where most kimberlites originated must be abandoned. This is justified by the occurrence of fragments of subducted oceanic lithosphere as eclogite xenoliths in kimberlites from the Colorado plateau (Helmstaedt and Doig, 1975) as well as by the distribution of Tertiary magmatic rocks in the southwestern United States that suggest the former existence of a shallow-dipping subduction zone in this region (Dickinson and Snyder, 1978). The fact that a similar "flat-plate" subduction model was proposed by Lock (1980) for the formation of the Cape Fold belt warrants a new look at Sharp's original hypothesis.

Two independent questions are pursued:
1. Did such low-angle subduction occur under Southern Africa and if so, are the kimberlites related to it?

2. Do xenolith suites of these kimberlites include possible samples of subducted material?

1. Both Sharp and Lock relate the Permian to Middle Triassic Cape folding to subduction under Gondwanaland prior to its breakup, when according to Sharp " ... the oceanic plate associated with this orogeny dived to great depth and went hundreds of kilometers inland underneath the former continent". As folding in the Cape Fold belt was broadly contemporaneous with the opening of the Tethys ocean we suggest that spreading of the Tethys caused the increase in plate convergence rates necessary to initiate low-angle subduction along the southern margin of Gondwanaland.

A compilation on a map of the reconstructed Gondwana continent shows that the distribution of kimberlites is considerably less random than suggested by distribution maps using the present configuration of continents. A broad zone of kimberlites cuts numerous different geological provinces and lies parallel to the belt of Late Paleozoic igneous rocks stretching from South America past South Africa, through Antarctica to Australia (Samfrau geosyncline of DuToit, 1937). In South America and Southern Africa the southwestern boundary of this kimberlite belt lies between 1500-2000 km cratonwards from the assumed Late Paleozoic to Triassic continental margin. Although the timing of the kimberlite eruptions (between 79 and 133 m.y., Davis, 1977) approximately coincides with the break up of Gondwanaland, the southwestern margin of the belt shows no relationship to the orientaion of the South Atlantic rift. Similarily, a correlation with transform faults, as proposed by Williams and Williams (1977) for West African kimberlites, is not obvious. In a subduction model the time lag between subduction and kimberlite emplacement may be explained as a consequence of the emplacement mechanism. If kimberlites traverse the lithosphere along stress corrosion fractures (Anderson, 1979), emplacement was not possible until Gondwanaland became an extensional regime. Scatter in timing of kimberlite eruptions can be explained by differences in lag times following cessation of subduction that are a function of variations in thermal gradients within the sub-continental mantle as well as local structural conditions.

A subduction model for the Mesozoic kimberlites in Southern Africa must also account for the Karroo magmatism, as there is a common regional association of kimberlites with Karroo dykes and sills. Isotopic data appear to suggest that tholeiitic flood basalts are derived from continental

lithosphere (Allegré et al., 1981; 1982), whereas kimberlites and alkali basalts come from a deeper source which at present cannot be identified as typically sub-oceanic or sub-continental. It is therefore possible that Karroo magmatism was triggered by subduction (Cox, 1978) below the continental lithosphere, and that the later kimberlites shared the same fracture systems as access routes to the surface.

2. Although Late Paleozoic to Triassic low-angle subduction may have supplied volatiles for the formation of the Cretaceous kimberlites, actual samples of this young subduction zone have not been identified among the various xenoliths of Southern African kimberlites. However, chemical arguments and relics of prograde metamorphic reactions suggest that certain eclogites are subducted metabasites, and the different ages of such eclogites from Robert Victor (⌐2.5 b.y.; Kramers, 1979) and the Karroo kimberlites (⌐1 b.y., Robey, 1981) imply sampling of remnants of at least two earlier subduction episodes. Milashev (1973) interpreted the regional zonation of kimberlites and their xenoliths from the diamond subfacies to the pyrope subfacies as evidence for ascending convection currents under the diamond-bearing province. We consider it more likely that the zonation apparent in South African xenoliths reflects processes related to the Precambrian subduction under, and the accretion of continental fragments to the Archean Kaapvaal craton. This interpretation is consistent with the observations by Griffin et al. (1979) that nodules of garnet granulites and "crustal" eclogites are common in kimberlites around the edge of the Kapvaal craton, but are not obvious in kimberlites within the craton.

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H20 DIFFUSION DATA AND THEIR BEARING ON THE INTERPRETATION OF MANTLE NODULES AND THE EVOLUTION OF THE MANTLE LITHOSPHERE.

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A common assumption in the interpretation of the ultramafic nodules erupted with kimberlitic and basic igneous magmas is that their mineralogy reflects the ambient pressure-temperature conditions of either their location in the mantle immediately prior to eruption or conditions obtaining during their entrainment. Considerations of nodule petrology and diffusion data suggest that this assumption needs modification for the upper part of the mantle lithosphere.

The erupted ultramafic nodules indicate that a major part of the mantle lithosphere consists of moderately coarse-grained (around 2mm or more) assemblages of anhydrous minerals (olivine, orthopyroxene, clinopyroxene, garnet, spinel). The amounts of biotite or amphibole present in the rocks prior to interaction with the transporting kimberlitic or other melt usually appears to be very small; and there is generally little evidence of the presence of a pervasive volatile phase. The achievement and maintenance of chemical equilibrium within and between the crystals in such rocks will be dependent on diffusion and, in the absence of deformation, presently available volume diffusion coefficient data for anhydrous conditions should be applicable. An extract of such data is given in figure 1 for the minerals and diffusing cations indicated in the figure; solid lines refer to the temperature range of the experiments involved and the dashed lines are extrapolations to lower temperatures. The numbers against each line indicate the

source of the data as given in the reference list at the end of the paper.

The approximate magnitude of the diffusion coefficient necessary to achieve and maintain equilibrium compositions in crystals may be calculated using the relation $D \approx x^2/t$ (Kingery et al. 1976, p. 226); where D is the diffusion coefficient, t is time, and x is distance. In figure 1 the horizontal lines show the D values appropriate to certain distances (in mm) and times (in Ma) according to the above equation, and the minimum temperatures necessary for these D values may therefore be determined from figure 1. Thus for pyroxene crystals figure 1 indicates that equilibration of Ca-Mg across a distance of 1mm (representing margin to core distance) in times ranging from 10 to 100 Ma will require temperatures approximately in the range 1050 to 950°C. It should be noted that the pyroxene D values (in figure 1) leading to these temperature estimates do not appear to be unreasonably small when the large number of 'null' experiments on pyroxene diffusion are considered (Freer et al., in press). Relative to this pyroxene data, figure 1 shows olivine Fe-Mg diffusion to be extremely fast. Of the two sets of Fe-Mg garnet data shown the low temperature extrapolated values of line 4 (Fig. 1) are in reasonable agreement with estimates based on natural rocks (Lasaga et al. 1977). Ca diffusion in garnets appears to be somewhat faster (Duckworth and Freer 1981). Little data is available for trivalent cations in silicates, but in spinels Al and Cr com-
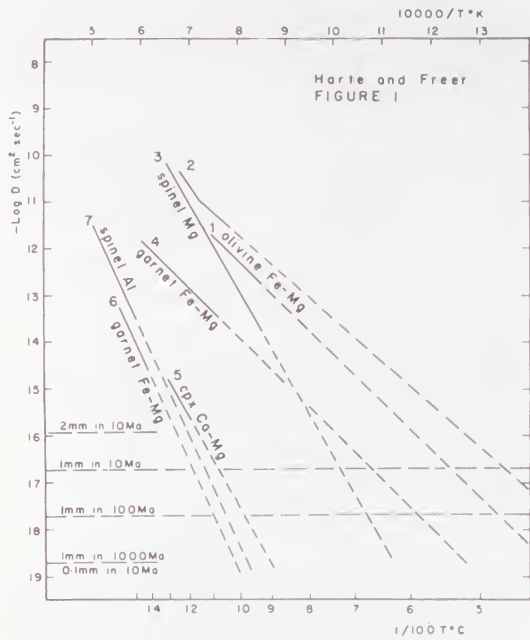
Harte and Freer
FIGURE I

monly diffuse more slowly than divalent cations
(Freer 1980).

For coarse ultramafic mineral assemblages the dif-
fusion data suggests that major aspects of mineral
chemistry will be unable to equilibrate in time peri-
ods of several hundred million years unless tempera-
tures exceed about 900°C. Some divalent cation dif-
fusion, such as Fe-Mg in olivine and probably in gar-
net will however be effective at lower temperatures.
The rough guiding temperature of 900°C receives some
support from the restricted transformations shown by
coarse-grained anhydrous rocks in granulite facies
crustal metamorphism (e.g. McLelland and Whitney
1980). Estimated geotherms for continental shields
and platforms, and ocean basins (e.g. Clark and
Ringwood 1964) indicate that temperatures around
900°C do not occur until significant depths beneath
the Moho; the uppermost mantle lithosphere may thus
contain largely frozen mineral compositions which are
unlikely to yield consistent T-P data appropriate to
their ambient T-P conditions. This conclusion pro-
vides a possible explanation for the commonly ob-
served lack of ultramafic nodules which yield T-P
estimates characteristic of the uppermost mantle
lithosphere in stable tectonic regions.

The textures of the coarse ultramafic nodules of-
ten show little evidence of their petrogenetic histo-
ry. Some preferred mineral orientation may occur,
and there is the occasional occurrence of exsolution
lamellae suggesting reasonably slow cooling at high
temperatures. The temperatures estimated for the
coarse rocks by various geothermometers (e.g.
Carswell and Gibb 1980a) are dominantly in the range
1100 to 800°C. The overlap of this temperature range
with the approximate minimum temperatures estimated
above for diffusional equilibration suggests the
strong possibility that many of the temperatures es-
timated by geothermometry are 'blocking' temperatures
for diffusion in moderate to slow cooling. Carswell
and Gibb (1980a, fig. 2) compare the estimated tem-
peratures yielded by equilibria involving: two pyro-
xene Ca-Mg exchange, garnet-pyroxene Fe-Mg exchange,
and garnet-olivine Fe-Mg exchange. In terms of the
diffusion data of figure 1 the last of these equili-
bria may be expected to equilibrate at the lowest
temperatures, and it is this geothermometer which
yields the majority of temperature estimates below
900°C (Carswell and Gibb 1980a, fig. 2). This corre-

lation must be treated circumspectly because of de-
pendence of the extent of cation exchange on other
factors (distribution coefficients, diffusion coeffi-
cient ratios and cooling rates) beside self-diffusion
coefficients (Lasaga et al. 1977). However, we con-
sider it most likely that the mineral compositions in
many coarse nodules were frozen long before eruption,
rather than being quenched in the rocks at the time
of eruption. Thus many of these nodules may have
been erupted from relatively shallow depths, and even
from immediately beneath the Moho, in the upper man-
tle. These inferences provide an explanation for the
relatively narrow ranges of temperature estimates ob-
tained from coarse nodules.

It follows from the above arguments that the rocks
occupying the uppermost mantle over a major part of
the lithosphere must be the cooled relics of events
dating back to a time when the mantle section con-
cerned was subjected to a major tectonothermal dis-
turbance. This may have been connected either with
the hot and dynamic environments associated with
lithospheric plate boundaries or with a major intra-
plate thermal perturbation associated with igneous
activity and/or lithosphere attenuation. Tempera-
tures in excess of 800°C (the lowest geothermometry
estimates for nodules) must have existed near the
crust-mantle boundary at the time of the tectonther-
mal event concerned. Such temperatures are clearly
acceptable where the event has involved extensive
basic - ultrabasic magmatism. In orogenesis, tempera-
tures of 800°C and higher may occur at the base of
the crust both with crustal thickening by magma ad-
dition (Wells 1980) and with tectonic crustal thick-
ening (even without abnormal mantle heat flows -
England 1978). The common occurrence of temperature
estimates of 700 to 900°C for granulite facies rocks
often believed to form the lower crust accords with
the above considerations, as does the continuity of
temperature estimates for alpine-type and mantle-
derived garnet peridotites (Carswell and Gibb 1980b).

Following from the above, it appears that the ap-
proximate compatability of T-P estimates of coarse
nodules from kimberlites with the Clark and Ringwood
(1964) shield geotherm (Boyd 1973; Carswell and Gibb
1980a) is partly a result of the coincidence of that
portion of the geotherm concerned with the cooling
temperatures imposed by diffusion. The low dT/dP
slope given by the coarse nodule estimates may result
from the differences in 'blocking' temperatures of T-
dependent and P-dependent mineral equilibria, and the
dependence of the P estimates on T estimates (Fraser
and Lawless 1978).

The temperature estimates of 1200 to 1400°C given
by the high temperature deformed peridotite nodules
from kimberlites must have a generally different sig-
nificance to the temperature estimates from coarse
nodules. At the high temperatures indicated these
deformed rocks would equilibrate rapidly (fig. 1)
especially in the case of neoblasts with grain sizes
around 0.1mm. Relatively rapid quenching of these
rocks is therefore indicated, and this accords with
an origin closely associated with eruption (Mercier
1979).

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AUTHOR INDEX
for the
KIMBERLITES

S. Akimoto in San Carlos during Navajo field trip.
Photo C. Froidevaux.

CO$_2$-CO FLUIDS IN A VEINED NODULE (NEVADA) : IMPLICATIONS FOR OXYGEN FUGACITY.

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A wehrlite nodule from the Marcath flow, a late Cenozoic alkali basalt of the Lunar Crater volcanic field (LCFV), contains a 1 cm wide vein (80 % amph, 15 % fspar (An50), and 3 % ilm) which chemically resembles an alkali basalt. The vein has been interpreted to result from the intrusion and subsequent crystallization of a relatively primitive alkali basaltic magma into a wehrlite mass in the upper mantle or lower crust (BERGMAN et al., 1981, EPSL, 56, 343). CO$_2$-rich fluid inclusions occur in fspar, cpx, ol, and amph in both the vein and host wehrlite. By Raman spectroscopic analysis, CO is identified only in the vein fluids. Using the CO-CO$_2$ fluid compositions and fugacities, oxidation states of the fluids in the vein phases are near QFM (log fO$_2$ = -9 at 1200°C), whereas, those in the host wehrlite are more oxidized (logfO$_2$ > -7). On cooling below 1000°C, the CO-CO$_2$ fluids reaches the stability field of graphite. Inside the inclusions, the lack of graphite and the presence of CO prooves that these fluids can be considered as "quenched" fluids and hence are suitable for isochore and chemical equilibrium computations.

The fO$_2$ of the vein fluid is in the range reported for basaltic extrusives and suggests that the vein's parental magma had an oxidation state at depth similar to surficial basaltic lavas. Fluids within the wehrlite are compositionally different from those in the vein and suggest that (a) these two fluid generations did not equilibrate over the scale of < 5 mm and (b) the primitive alkali basalt intruded a wehrlite significantly more oxidized.

COMPOSITIONS OF FLUIDS IN EQUILIBRIUM WITH PERIDOTITE AND IMPLICATIONS FOR ALKALINE MAGMATISM-METASOMATISM

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Calculations of the fO$_2$ of peridotic mantle from olivine-orthopyroxene-ilmenite assemblages indicates high-pressure oxidation conditions very close to the EMOD buffer:

$$log\ fO_2 = 7.61 - 23872/T + 0.064(P-1)/T$$

These conditions, also near the MW buffer, are compatible with graphite or diamond stability, and, most importantly, with presence of fluids consisting of H$_2$O-CO$_2$, not H$_2$O-CH$_4$ or CH$_4$.

Solubilities in H$_2$O and H$_2$O-CO$_2$ fluids in equilibrium with enstatite-forsterite-phlogopite peridotite and enstatite-forsterite-diopside-spinel-amphibole peridotite have been determined at 15-20 kbar and 750-1100 C. Amphibole peridotite fluids principally contain silica, alumina, and alkalies in total amounts less than 3 wt % in H$_2$O fluids and 0.5 wt % in H$_2$O-CO$_2$ fluids. Phlogopite peridotite fluids are broadly similar but contain a minimum of 16 wt % solute. Such fluids could significantly alter local regions of the mantle deeper than about 90 km by alkali metasomatism, although alkalies are accompanied by approx. equal molar alumina and considerable silica.

The region near 90 km, near the lower pressure limit of the carbonate stability and the upper limit of amphibole stability, is the most likely region of significant fluid solute precipitation and metasomatic alteration. This region probably yields highly alkaline magmas but not kimberlites.

Fluids Coexisting with En-Fo-Phlogopite		
P(kb),T°C: 15,1080	20,1100	20,1100
X$_{H2O}$(v): 1.0	1.0	0.8
SiO$_2$: 72.2	71.3	64.8
Al$_2$O$_3$: 14.1	14.0	17.0
MgO: 5.3	5.6	3.5
K$_2$O: 8.4	9.1	14.7

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SOME NEW MINERALOGICAL DATA FOR THE MANTLE XENOLITHS OF ULTRABASIC ROCKS FROM YAKUTIAN KIMBERLITES WITH REFERENCE TO SOME ASPECTS OF THEIR DEEP-SEATED EVOLUTION

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The xenolith suite from Yakutian kimberlites contains wide variety of ultrabasic rocks: from extremely depleted chrome pyrope dunites to Mg-pyroxenites practically free of olivine. These rocks are represented by dunite, harzburgite, lherzolite and wehrlite parageneses. The Ca- content of the garnets from these rocks is less than 2 mol.% of Ca-component for dunite paragenesis reaching 56 mol.% of the Ca-component in xenoliths of garnet wehrlites, which are of very uncommon occurrence. The xenoliths of coarse megacrystalline rocks recently recovered from Udachnaya Pipe are especially interesting. The mineral compositions of 140 xenoliths, 11 of which are diamondiferous, were studied by microprobe method. The mineral compositions of xenoliths of diamondiferous coarse megacrystalline rock are totally plotted in the fields of the compositions of the minerals included in diamonds from Udachnaya Pipe. However, the variations in the mineral compositions of investigated xenolith suite of the coarse megacrystalline ultrabasic rocks were found to be much wider than those included in the diamonds from Udachnaya Pipe. The lower limit for the Cr_2O_3 content in chromites from these xenoliths lowers below 46,2 wt%, which is much lower than the values obtained for chromites included in the diamonds (61,4) and chromites from the diamondiferous xenoliths (61,7). The garnets from xenoliths of the coarse megacrystalline rocks are less rich in chrome to contain higher Ca compared with garnets from diamon-

diferous xenoliths (x Cr_2O_3 - 8,92;9,20; 10,52; x CaO - 3,67; 2,95;2,53 wt%.respectively). The garnets and olivines from xenoliths of coarse megacrystalline rocks contain higher Fe as a whole as compared with garnets and olivines associated with diamonds. In the coarse megacrystalline rocks as well as in the diamondiferous ultrabasic associations harzburgite-dunite paragenesis predominates (77,5%), the importance of lherzolite paragenesis is here somewhat higher (15,8% included in diamonds - 13,3%), and, especially wehrlite paragenesis (6,7%, inclusions in diamonds - 1,7%). The diamondiferous coarse megacrystalline xenoliths belong as a whole to harzburgite-dunite paragenesis.

Essential variations in the garnet compositions have been established for five xenoliths within a single sample. The widest variations in the CaO contents are (1,1-7,8 wt%) and Cr_2O_3 (8,1-13,4 wt%). A change in the paragenesis within a single sample from dunite type to wehrlite has been fixed.

The analysis of the conditions of equilibrium inherent to xenolith suite of the ultrabasic rocks as a whole has shown that their formation had taken place within the depths from 40 to 250 km. Also, there were obtained some evidence indicating the possibility of significant vertical ascent of the Mantle matter at the period of time preceding kimberlite formation. To these belong: 1) essential variation in the equilibration parameters, fixed by specific peculiarities in the composition and mineral structure inherent to some definite xenolith types; 2) the nature of exsolution textures of the garnets and pyroxenes;3) change of parageneses of the newly formed minerals to appear in the rocks in some new conditions. The obtained data are also indicative or 1) some of the varieties of the coarse megacrystalline ultrabasic rocks are the host rocks for predominant part of the diamonds; 2) the variations in the compositions, parageneses and exsolution of minerals in xenoliths are due to the solid-state reactions to occur owing to the variation in the P-T parameters of equilibrium, associated possibly with the peculiarities in the dynamic evolution of the Mantle matter.

COMPOSITION OF POLYMINERAL INCLUSIONS IN NATURAL DIAMONDS AND THEIR SIGNIFICANCE

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Since the time when original data were obtained for unusual Cr-rich, Ca-poor garnet compositions, both from African and Yakutian diamonds, special importance was attached to the search and examination of individual inclusions and combinations of various minerals contained in diamonds. The most reliable information for the nature of parageneses in diamondiferous environment may be derived from inclusions consisting of polymineral ingrown crystals inside the diamonds. The inclusions of this sort with distinctly displayed negative diamond morphology very often consist of two minerals. Three-mineral inclusions are not so common, whereas four-mineral ones are quite unique. Special study permitted one to fix the four-three-and two-mineral inclusions, which occur in Yakutian diamonds to detalize the well known common types of parageneses: ultramafic(peridotic) and eclogitic.

The data obtained for the mineral composition of four-mineral octahedral crystal from the "Aikhal" Pipe diamond (enstatite+olivine+pyrope+chromite) as well as three-mineral intergrowths from the Mir Pipe diamond (enstatite+pyrope+chromite) and (olivine+pyrope+chromite) have justified a self-independent nature of dunite-harzburgite paragenesis with analogy between the mineral composition and xenolith minerals of diamondiferous harzburgite from Udachnaya Pipe. The main peculiarity in the mineral composition of this paragenesis is high Cr_2O_3 in garnets (7-20%) and low CaO (1-3%)

resulting in high knorringite admixture (20-60%).

A characteristic feature for lherzolitic paragenesis is the presence of diopside along with olivine. Diopside was found to occur in the following polymineralic intergrowths: diopside+enstatite+olivine; diopside+pyrope; diopside+olivine; diopside+enstatite+olivine; diopside+enstatite. Pyrope from this association has moderate CaO (4-6%) and normally low Cr_2O_3. Typical polymineralic intergrowths were also found to occur in eclogite type parageneses: garnet+omphacite; garnet+rutile; garnet+sulphide; coesite+sulphide. All the ingrown crystals as well as ultramafic type have octahedral morphology.

Presence of polymineralic inclusions in diamonds is unambiguous proof in favour of equilibrated nature of crystallization of diamond and associated minerals. Variable nature of intergrowths and all the variety of parageneses established from their studying indicate the complex composition of the Upper Mantle beneath the platforms up to the depth of 250 km.

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OCEANIC CARBONATITES

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Carbonatites are commonly believed to be restricted to continental crustal regions and particularly to cratonic areas. That belief is false: carbonatites abound on nearly all oceanic islands where strongly alkaline plutonic igneous rocks are exposed.

In the Cape Verde Islands in the Central Atlantic Ocean 500 km off the west coast of Africa, intrusive carbonatites occur on the 8 islands where intrusive 'basement' is seen. Likewise, carbonatitic intrusive complexes are known on the Canary Island of Fuerteventura which is the only island in the Canary group with extensive plutonics. In all cases, the carbonatites are associated with ijolitic intrusive complexes, the volumetric proportion of carbonatite to ijolite being very variable. On the main island of Santiago in the Cape Verdes, there are three separate carbonatitic complexes, one of them also showing extrusive carbonatites.

The geochemistries of oceanic and continental carbonatites appear to be similar. Both are rich in the incompatible elements, particularly Sr, Ba, Nb and REE. Oceanic and continental ijolites and nephelinites are likewise similar.

The similarities indicate that the origin of these alkaline igneous rocks is independent of the presence of continental lithosphere, and that the source must lie deep in or below the asthenosphere.

However there is one criterion which distinguishes oceanic from continental carbonatites: the fenitization. Continental carbonatites at high levels in sub-volcanic intrusive complexes normally show intense potassium metasomatism with the development of much phlogopite and K-feldspar. The feldspathisation is normally accompanied by much brecciation. Oceanic carbonatites also show intense local phlogopitisation within the intrusive centre, but surrounding them is a wide zone in which albitisation takes place along fracture planes, dykes or other channelways through which fluids can migrate easily. X-ray and electron micro-probe studies show that, in both occurrences, the feldspars (commonly Or_{95} and Ab_{99}) were formed at low temperatures ($< 500^{\circ}C$) as appropriate to fluids emanating from carbonatite magma. Thus oceanic carbonatite magmas may be characterised by high Na/K ratios whereas continental ones have lower Na/K ratios.

A second possible distinction is the total absence of kimberlite from the oceans, whereas on the continents they are sometimes associated with carbonatites.

MAGNETIZATION IN CRUSTAL AND UPPER MANTLE XENOLITHS

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By measuring the magnetic properties of the upper mantle and lower crustal xenoliths, we can gain insight into the magnetization of otherwise inaccessible regions. The identification of magnetic boundaries associated with magnetic mineral variations, in the crust, and the magnetic contrast between the crustal granulites and the upper mantle peridotites, are specific insights attainable via laboratory study of xenoliths. Routine measurements, which magnetically characterize the xenoliths, have been performed, and in addition measurements such as susceptibility vs temperature, and elevated temperature viscosity provide insight into magnetic behavior at increasing depth, recognizing the existence of the geothermal gradient. Xenoliths from different tectonic provinces (rift zones, continental intraplate regions, converging plate margins) have been evaluated.

Thermal demagnetization of the NRM in ilmenites from Monastery and Frank Smith, indicate blocking temperatures ranging from ~200°C to ~550°C. The ilmenite phase in the ilmenite-pyroxene intergrowths has an extremely fine exsolution pattern observable at high magnification. Peridotite xenoliths from all other environments have 560-560°C Curie points indicative of magnetite. Thermal demagnetization of the natural remanence is utilized to evaluate whether the xenoliths have been altered at temperatures ≲550°C. No exotic mineralogies have been identified in any of the xenoliths studied. Chromite spinels and magnesian ilmenites dominate in peridotites from below the Moho and FeTi oxides dominate in crustal lithologies above the Moho. Certain granulite xenoliths from Bournac pipe and the Rio Grande rift exhibit magnetic self reversal properties, tentatively associated with the ilmenite

mineralogy.

Studies of the xenoliths provide evidence: that the Moho may be a magnetic boundary, that mafic-ultramafic granulite grade rocks are the significant magnetic rocks in the crustal column, that the fO_2-T conditions at depth, in rift zones and converging plate margins where the geothermal gradient is steep and the environment anhydrous, is responsible for crystallizing oxide minerals with Curie points < 300°C.

Magnetic properties of xenoliths are used to infer the distribution of crustal magnetization.